PALEOKARSTIC PHENOMENA, DEPOSITIONAL ENVIRONMENTS, AND DIAGENESIS OF THE LOWER ORDOVICIAN WEST SPRING CREEK FORMATION, ARBUCKLE GROUP, IN SOUTHERN OKLAHOMA

By

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"I don't know what I may seem to the world, but, as to myself, I seem to have been only like a [child] playing on the sea shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

Isaac Newton

DEDICATION

This thesis is dedicated to the memory of my mother,
Irene Musselman.

CHAPTER 1

INTRODUCTION

Setting

The Lower Ordovician West Spring Creek Formation of the Arbuckle Group is only a small part of an enormously thick sequence of carbonate rocks present in the Southern Midcontinent. This and other Ordovician formations form one of the most nearly complete sections of rocks of this system found on the North American continent, largely due to the fact that large amounts of sediments were deposited in subsiding basins. Subsidence and sedimentation were not constant, but varied in response to sea level changes due to climatic and/or tectonic variations. Carbonates were deposited in shallow, epeiric (epicontinental) seas covering much of the craton. Sea-level fluctuations are suggested by repetitive shallowing-upward sequences. If the shallowing-upward pattern continued until subaerial exposure, various episodes of karstification may have resulted. Shallowing-upward sequences characterize the West Spring Creek Formation, and indeed, most of the Arbuckle Group.

Late Paleozoic (Pennsylvanian) deformation resulted in uplift and erosion of the Arbuckle anticline, exposing the buried sediments and basement rocks. Recent epeirogenic uplift has resulted only in a gentle rise in elevation with little or no deformation of these rocks.

Outcrops of the West Spring Creek Formation exposed by road cuts in the Arbuckle Mountains were the principal areas of investigation for this thesis. The most magnificent exposures are along Interstate 35, and much of the detailed work has been done at these outcrops. However, the type locality for the West Spring Creek Formation, named after the West Spring Creek at the west end of the Arbuckle Mountains, is approximately three miles north of Springer on U. S. Highway 77 (Ham, 1950).

Purpose of Study

Recent discoveries of extensive gas reserves in the Arbuckle suite of rocks in Oklahoma (Petzet, 1989 and Hagar, 1989) and in rocks of equivalent age in nearby areas, such as the Ellenburger Group in Texas (Loucks and Anderson, 1985) and the Knox Group in Tennessee (Raymond and Osborne, 1991), appear to be in reservoirs with enlarged secondary porosity, in karstic zones. The age, extent, and types of recent karstification and paleokarst are, therefore, of interest to many geologists in the petroleum industry. Other researchers (McCracken, 1964; Harlton, 1964; Latham, 1968; Lynch and Al-Shaieb, 1991; Derby et al., 1991; Land et al., 1991; Carpenter and Evans, 1991; Wilson et al., 1991; and Waddell et al., 1991) have investigated and described various aspects of the West Spring Creek Formation from sub-surface data. Significant mapping has been done (Ham, 1950, 1954), and the outcrops have been logged painstakingly (Fay, 1969). The intent of this paper is to describe the depositional environment of the West Spring Creek Formation in detail, to investigate the intra-Arbuckle paleokarst as a logical culmination of the shallowing upward sequences, and to attempt to decipher the paragenesis related to the development of paleokarst.

Previous Investigations

The Arbuckle Group has been studied extensively by many researchers, partly because sparse groundcover allows reasonably good exposures of many formations, and partly because deep roadcuts have revealed nearly continuous sections of many of the formations. William Ham's (1950) doctoral dissertation is one of the best-known papers on the area, and Robert Fay's detailed 1969 roadlog is still in use as a field-trip guide.

Paleokarst has been studied in detail in Texas in the Ellenburger Group, which is of equivalent relative age, by Charles Kerans (1989) and Ijirigho and Schreiber (1986), but little has been published on the Arbuckle paleokarst. In 1928, in describing the Arbuckle limestone, Decker and Merritt documented post-Permian to recent karstification in southern Oklahoma. Caves were mapped in a cursory fashion by spelunkers during the 1920's. Breccias and megabreccias were described in the Kindblade Formation in the Arbuckle Mountains in an unpublished Master of Science thesis by Tapp (1978), and similar features were reported in the Cool Creek Formation by Ragland and Donovan (1985). "The World's Smallest Oilfield?" by Donovan (1987) actually describes a small Permian paleokarstic reservoir on Bally Mountain in southwestern Oklahoma.

Numerous disconformities or erosional surfaces have been documented by various authors, notably by Derby (1991). However, the relationship between these surfaces and the formation of paleokarst was not addressed until recently when Lynch (1991) documented many paleokarstic features in Arbuckle cores from the Ardmore and Marietta basins in southern Oklahoma and from the north-central Oklahoma Platform.

Methods and Procedures

The south flank of the Arbuckle Anticline, where the most extensive section of the West Spring Creek is exposed, offers the best access to and the most variety of the specific features I wished to investigate. The cyclicity and the sub-aerial exposure represented by the red beds, in particular, are not as clearly defined on the north flank of the anticline. Here, the West Spring Creek is severely truncated by a major fault which juxtaposes the Cambro-Ordovician Arbuckle against Pennsylvanian Collings Ranch Conglomerate. Some red beds and paleokarst are evident and were documented, however,to be used in comparative studies with the area of principal scrutiny.

Initial investigations of the West Spring Creek Formation entailed examination of the outcrop (described by Fay in 1969) located on the south flank of the Arbuckle anticline. Thin sections were made from specific beds selected principally by changes in lithology, in order to establish a certain specificity with respect to the depositional environment and to delineate the diagenetic history. One particular shallowing-upward sequence was selected for more detailed investigation.

The most clearly defined red-bed sequence was chosen for bed-by-bed analysis to facilitate a description of the paleokarstification. A detailed log was made of this red-bed sequence, and thin sections were made from strata selected by changes in lithology, cement, or color. Other red-bed zones were examined in a more cursory fashion to ascertain if the paleokarstic features are present in these areas as well. Photomicrographs and outcrop photographs were taken, as well as photographs of the hand samples before and after slabbing.

One core, the Amoco SHADS #4 from Rogers County, which encompasses the strata from near surface to basement, was obtained from the Core Library in Norman, Oklahoma and logged to provide a subsurface stratigraphic equivalent to rocks exposed at the surface. Thin sections were made from a few selected zones believed to be indicative of karstification or erosion.

The determination of the paragenetic sequence of the West Spring Creek Formation was based on petrographic analysis such as routine microscopic examination, X-ray diffraction, and X-ray fluorescence.

The carbonate-rock classification used in this paper is largely from the Dunham (1962) system, but Folk's (1962) terms lend themselves quite well to microscopic analysis, and for this reason were also utilized where applicable.

CHAPTER II

REGIONAL GEOLOGY OF ORDOVICIAN CARBONATE ROCKS

Stratigraphy and Locale

The carbonate rocks of the West Spring Creek Formation constitute the uppermost Ordovician unit of the Cambro-Ordovician Arbuckle Group (Figure 1). They were deposited during the subsiding stage of the Southern Oklahoma aulacogen as marine waters transgressed the developing continental margin and adjacent trough (Johnson, 1991). Underlying the Arbuckle Group (not shown in Figure 1) is the Upper Cambrian Timbered Hills Group (the Honey Creek Limestone and the overlying Reagan Sandstone) which is unconformable on igneous basement rocks.

The 6700-foot-thick Arbuckle carbonate section is predominantly limestone and contains only minor amounts of shale, sandstone, and dolomite (Ham, 1950). To the east and north of the aulacogen, dolomite is more common. The predominance of limestone within the aulacogen and dolomite on the craton suggests greater water depths along the trend of this trough (Wickham, 1978).

The four lower units of the Arbuckle Group, also Upper Cambrian, are the Fort Sill Limestone, the Royer Dolomite, the Signal Mountain Limestone, and the Butterly

Dolomite (Figure 1), although AAPG COSUNA (Correlation of Stratigraphic Units of North America) charts place the Butterly in the Ordovician. Some researchers (Ragland and Donovan, 1991; Ham, 1950) have suggested that locally the Royer and Butterly Dolomites are diagenetic alterations of the Fort Sill, Signal Mountain, and lower McKenzie Hill limestones. These dolomites probably formed as a result of hot basinal fluids invading the formations. In 1950, Ham characterized the Royer and Butterly as separate formations, and later other authors (Winland, 1956; McDaniel, 1959), listed eight formations in the Arbuckle Group, which is now generally accepted. Overlying the Butterly are the McKenzie Hill, Cool Creek, Kindblade, and West Spring Creek Formations. In the study area the Arbuckle is overlain unconformably by the Middle Ordovician Simpson Group, although the unconformity is considered by some investigators (Reeder, 1974; Walters, 1958; and Lynch, 1991) to be much more obvious in areas away from the aulacogen. Derby et al. (1969, 1989), using paleontologic rather than lithologic characteristics, placed the Cambro-Ordovician boundary lower into the Signal Mountain. They also suggested that the Lower/Middle Ordovician boundary is well below the top of the West Spring Creek. However, this report will follow accepted definitions of boundaries (Ham, 1950; Fay, 1969; AAPG COSUNA, 1987).

Some of the most prominent, best-exposed upper Arbuckle outcrops are in Interstate 35 roadcuts through the

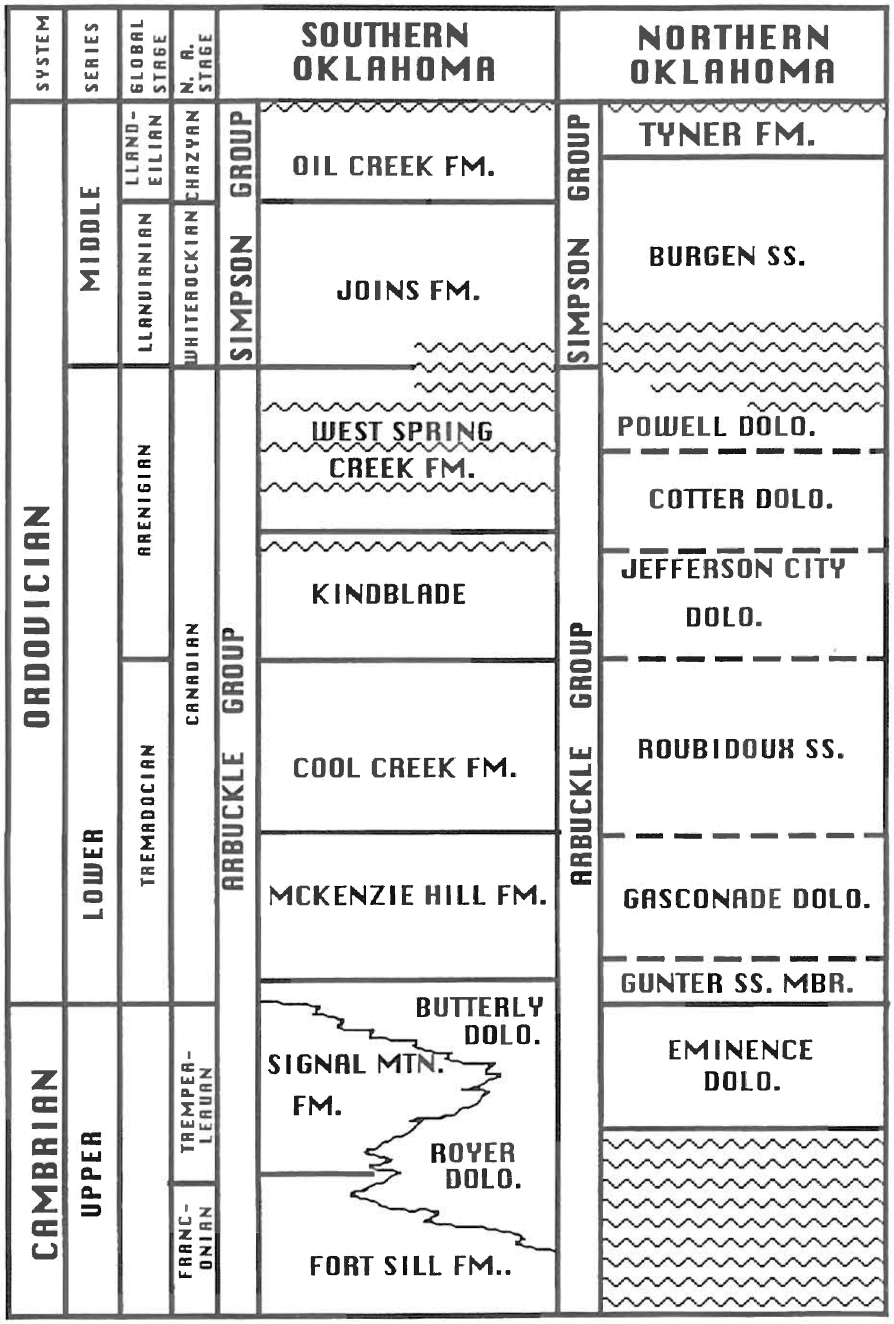


Figure 1. Stratigraphic section of the Upper Cambrian through the Middle Ordovician of Oklahoma. (Modified after Chenoweth, 1968; Ross et al.,1982; AAPG COSUNA, 1987; and Lynch, 1990).

Arbuckle Anticline (Donovan, 1991). The roadcuts are in the Arbuckle Mountains in northern Carter and southern Murray Counties (Figure 2). The anticline trends northwestward, and is a result of Pennsylvanian diastrophism (Wickham, 1978). It is doubly plunging and asymmetrical with an overturned north limb and a more gently dipping south limb. Significant faults in the vicinity are the Washita Valley Fault System and the Reagan Fault, which have regional trends of about N60W (Figure 3). Structural evidence suggests that these are strike-slip faults, as some of the folds in the area do not parallel the fault trends, but intersect them in a left-lateral sense (Wickham, 1978). It has also been suggested that the Pennsylvanian diastrophic activity could have reactivated normal faults associated with the rifting stage of the aulacogen (Wickham, 1978). Another series of minor, largely enigmatic faults (Cemen, 1994) are at high angles to the northwest-trending faults (not shown in Figure 3).

The Arbuckle Mountain uplift is an inlier of Paleozoic and Precambrian rocks encompassing approximately 1000 square miles and is characterized primarily by carbonate strata (Ham, 1950), with igneous basement rocks in the core of the anticline. It is bounded by the Ouachita foldbelt on the east, which is dominated by high-angle thrust faults of Pennsylvanian age. These faults probably are reactivated Cambrian normal faults (Wickham, 1978). To the south are the Ardmore and Marietta basins and to the west the gabbro-,

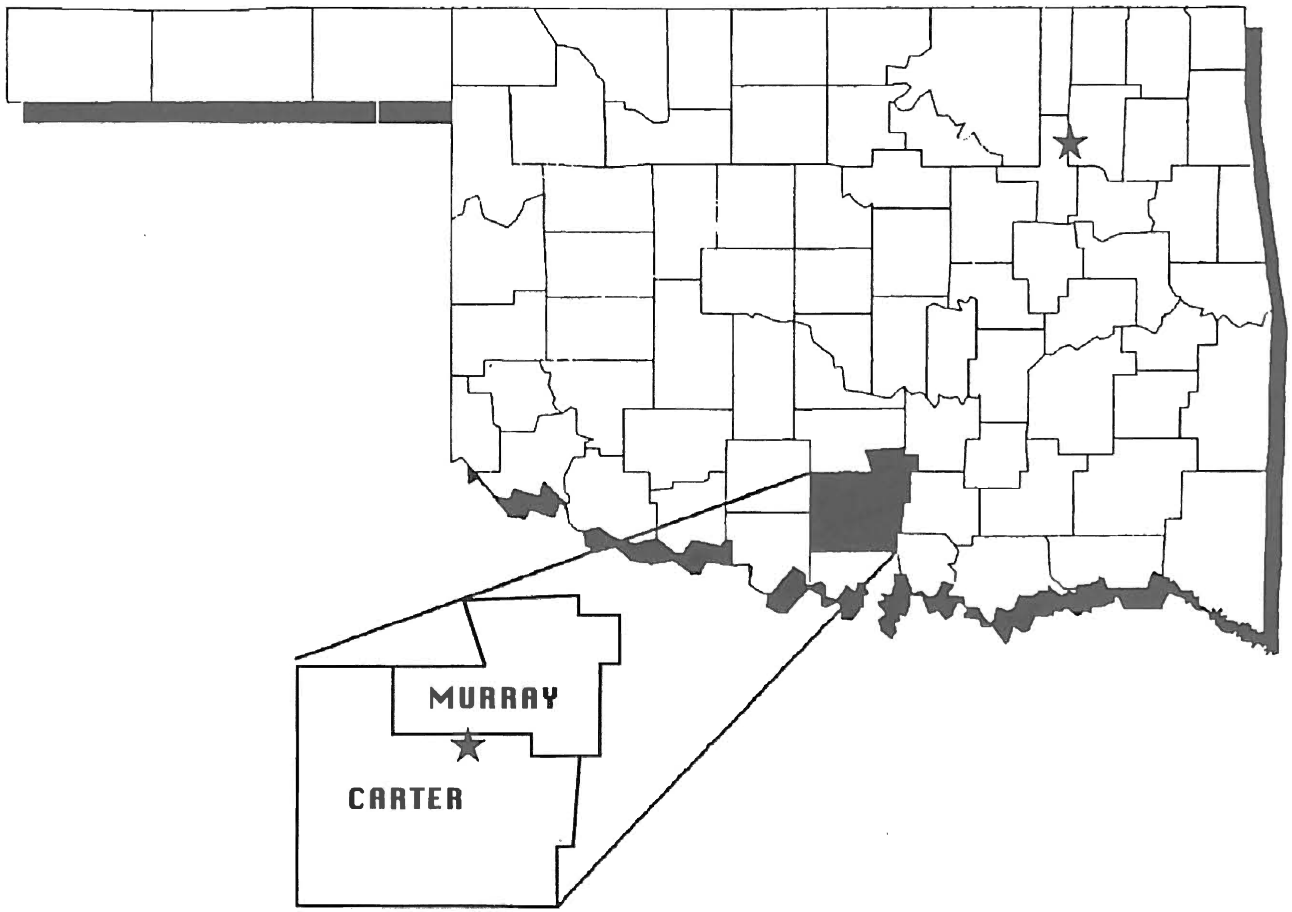


Figure 2. Map of the study area. Stars indicate approximate locations of Amoco core in Rogers County, northeastern Oklahoma, and outcrop studied in Carter County.

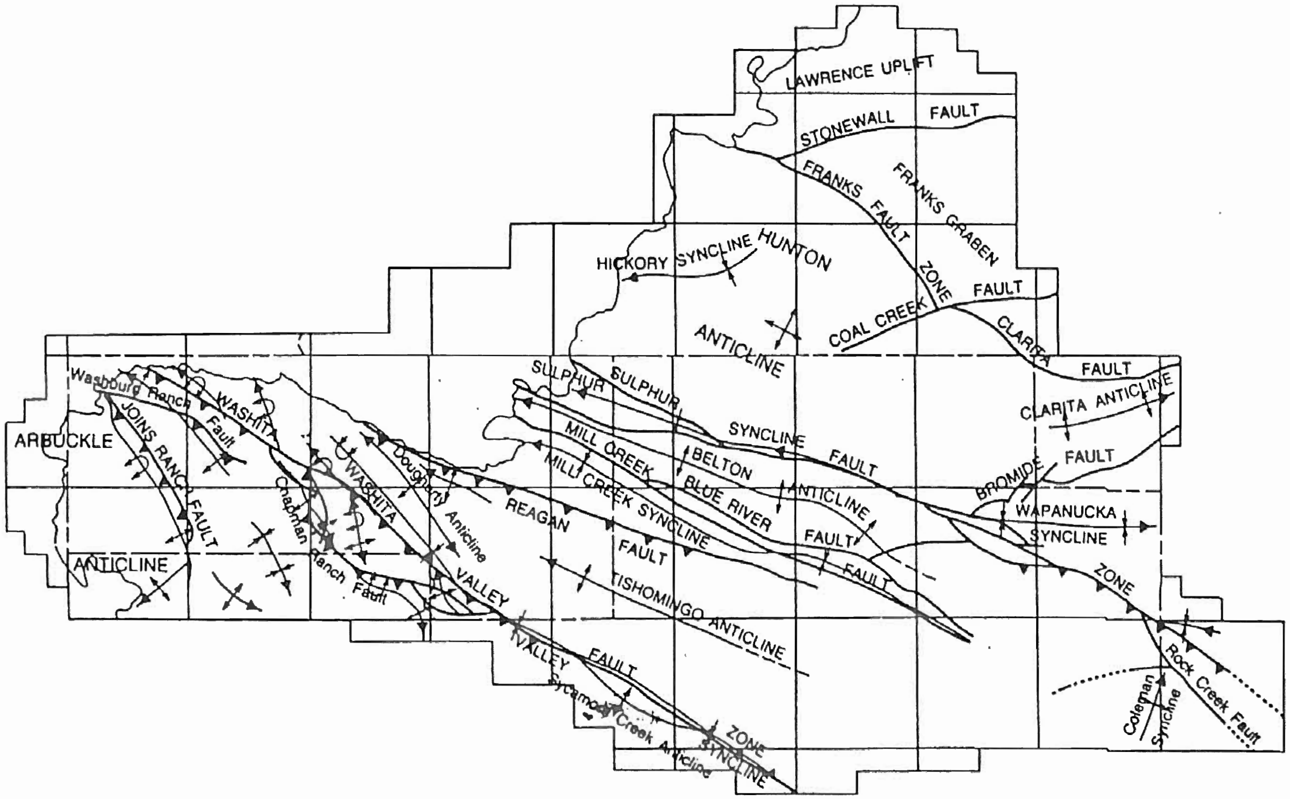


Figure 3. Index map of the Arbuckle Mountains, showing principal structural features (Oklahoma Geological Survey, 1990).

granite-, and rhyolite-dominated Wichita Mountains, the Criner uplift and the Anadarko basin, all of which are related to Pennsylvanian diastrophism. However, the Wichita Mountains igneous activity was earlier and these mountains are primarily remnants of the igneous activity associated with the rifting stage of the aulacogen; the remnants were uplifted during the deformational stage of aulacogen development. The Ouachita Foldbelt is a continental margin which was thrust to the northwest during the deformational stage (Wickham, 1978). To the northeast is the Arkoma basin, and the Hunton-Pauls Valley uplift is directly to the north (Figure 4). The crest of the Arbuckle Anticline is at the altitude of 1,377 feet, only 607 feet above the surrounding plains, but it is "six times greater than that of any other topographic feature between Oklahoma City and Dallas" (Ham, 1950).

Petrology of the Arbuckle Group

Arbuckle rocks are predominantly carbonates, consisting of various shallow-water limestone facies interfingered by and interbedded with dolomites, with minor amounts of sandstone. The sandstones are invariably fine-grained, well-rounded, well-sorted quartz arenites with little or no other detrital constituents. Ham (1950) reported a very low feldspar content in Arbuckle formations younger than the McKenzie Hill Formation. The tendencies of the grains to exhibit mainly straight extinction and to

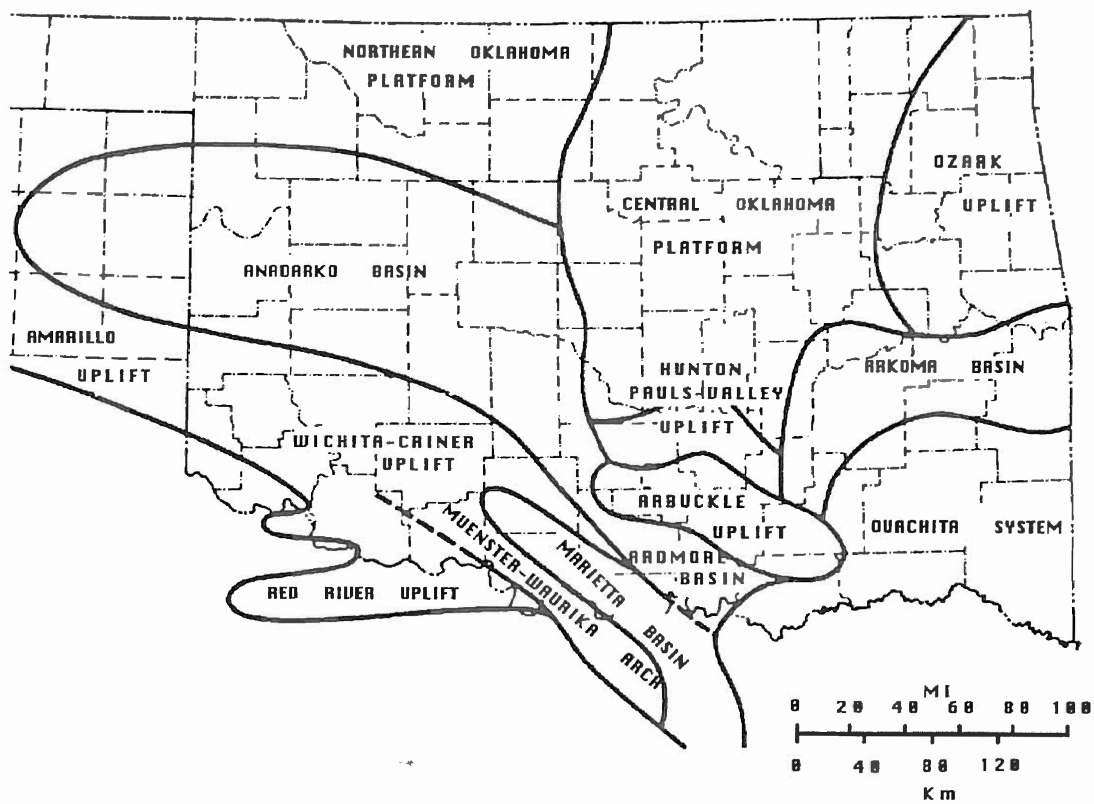


Figure 4. Tectonic map showing principal basins adjacent to Arbuckle Mountains (after Arbenz, 1956).

have few microlites or vacuoles indicate a probable plutonic origin. They tend to be well cemented with either calcite or dolomite. The basal sandstone, which marks the Kindblade-West Spring Creek boundary [on the Interstate 35 outcrop on the south flank of the Arbuckle Anticline], has alternating laminae of dolomitic sandstone and sandy dolomite, moderately indurated, with few structural features. Another sandstone overlies the uppermost red-bed sequence in the West Spring Creek. Figures 5 and 6 illustrate bimodal trough cross beds, which reflect tidal influences, and symmetrical ripple marks characterizing this stratum. It is primarily calcite-cemented, but the clastic constituents strongly resemble other sandstones within the formation. Most Arbuckle stratigraphic units have only two or three percent sand content (Ham, 1950), although in some formations sandstones are persistent enough to be stratigraphically significant.

The different types of limestone reflect their depositional environments. Facies ranging from subtidal massive mudstones and wackestones to shaly limestones or marls of tidal flats in the supratidal zones are throughout the shallowing-upward cycles of these formations. Also common within the upper Arbuckle Group are many varieties of algal structures or stromatolites.

Dolomites of the Arbuckle encompass a wide range of morphologies which are dependent, to a large extent, on their mode of crystallization and depth of burial. In

Figure 5. Bimodal trough cross-bedding (arrow) in the calcite-cemented sandstone that caps the uppermost red-bed sequence in the West Spring Creek Formation.

Figure 6. Symmetrical ripples in sandstone that caps the upper red-bed sequence.

1990, Lynch described eight types ranging from syndepositional and epigenetic to thermal dolomite, and classified them as either pore filling or matrix replacive dolomites.

CHAPTER III

DEPOSITIONAL ENVIRONMENTS AND DIAGENESIS OF THE WEST SPRING CREEK FORMATION

Local Setting

Upper Cambrian and Lower Ordovician Formations in southern Oklahoma were deposited in shallow, warm epeiric seas, which covered much of the North American craton over a period of about 45 million years. Figure 7 illustrates the paleogeography of these deposits, termed the "Great American Bank". This was located in areas east and south of the Transcontinental Arch, a positive topographic feature that probably would have drastically affected water circulation in the region. This arch most surely had a strong dampening effect on the severity of storms. The shallow seas might also have limited wave depth somewhat and hence their destructive capacity. These two factors may help to explain the relative paucity of storm deposits found in the West Spring Creek.

These carbonate rocks were deposited in a classic carbonate-ramp setting (Figure 8) with a slope of approximately a few centimeters per kilometer (Ahr, 1973; Irwin, 1975). The slope allowed relatively small fluctuations in sea level to affect very broad areas in the

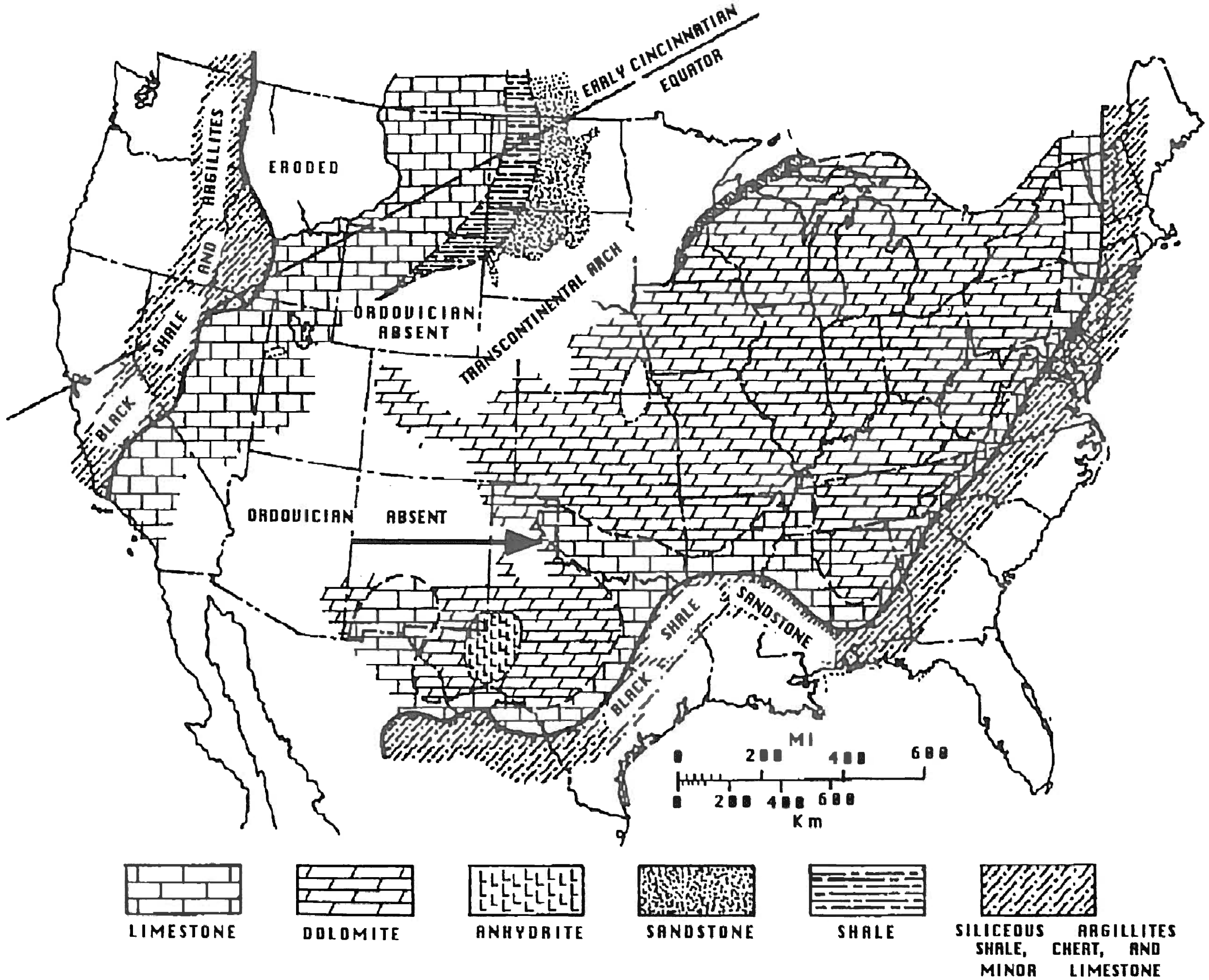


Figure 7. Distribution of Ordovician lithofacies of the western United States. Arrow indicates location of the Oklahoma aulacogen (after Ross, 1976, and Wilson, 1991) .

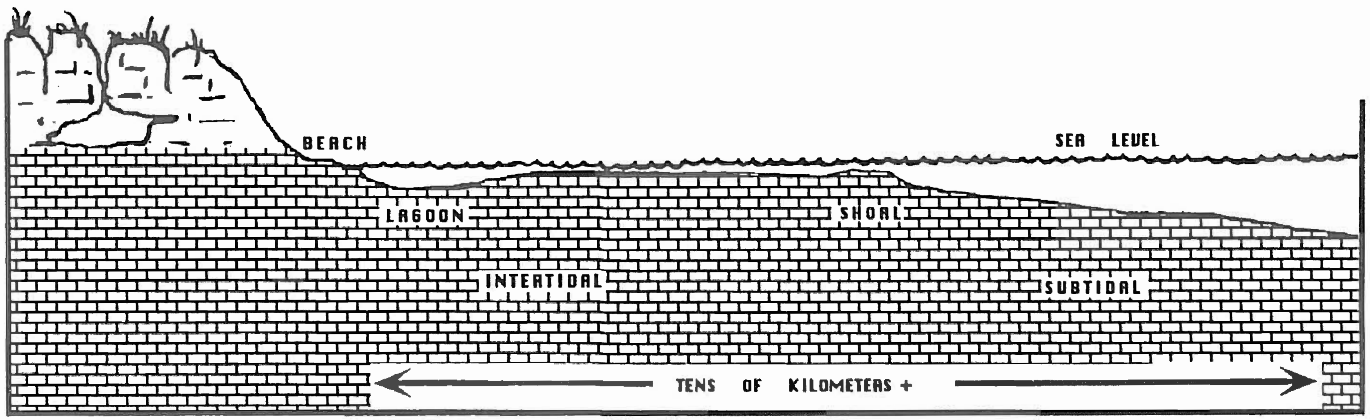


Figure 8. Ramp model of carbonate deposition (modified after Ahr, 1973; Irwin, 1975).

near-shore environments. In comparison, steeper gradients in a modern continental shelf environment would affect only a narrow band of deposits along the shore-line. Large areas of intertidal and supratidal zones would have been inundated with a rise of only a few feet in sea level. Conversely, lowering of sea level would have resulted in subaerial exposure with subsequent oxidation, dissolution and erosion of broad expanses of carbonate sediments. This could have occurred seasonally in response to annual fluctuations, or it could have had a broader time cycle. Evidence suggests that both situations existed. The laminated sedimentary features in the upper intertidal to supratidal facies (Figures 9 and 10) could represent annual fluctuations in climactic conditions, such as monsoons. The shallowing upward cycles embody a multiplicity of laminites as well as deeper water sediments deposited over longer periods of time (Wilson, 1993).

Depositional Facies

The West Spring Creek Formation is composed of nearly all of the common shallow-water carbonate facies. These carbonates were deposited in repetitive shallowing-upward sequences that could have resulted from fluctuations in sea level. These fluctuations resulted in the deposition of a wide variety of lithologic types, the character of which was largely dependent upon water depth and energy levels.

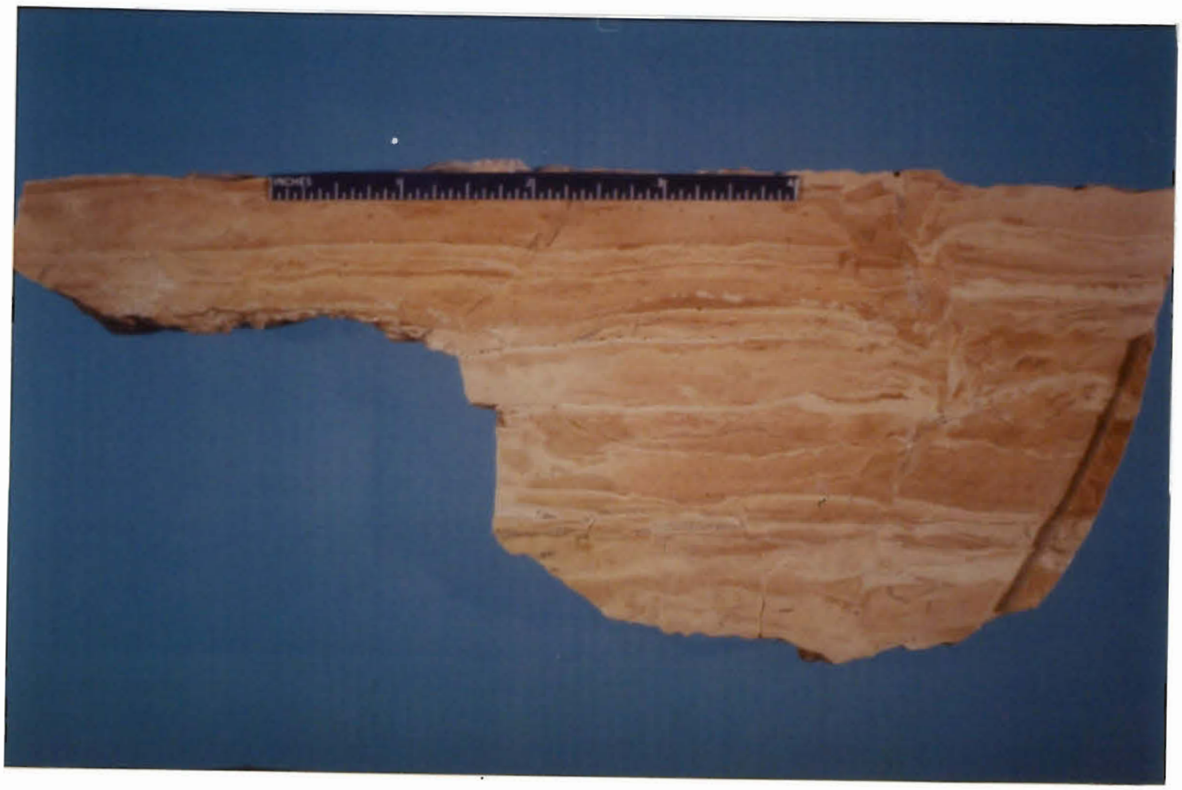


Figure 9. Photograph of hand sample of laminated deposits from an upper intertidal to supratidal, near-shore environment.

Figure 10. Photograph of hand sample of lamination in a tidal flat facies.

The facies observed in the West Spring Creek are:

1. Subtidal
2. Upper subtidal
3. Lower intertidal
4. Intertidal
5. Upper intertidal and lagoonal

Subtidal deposits, as shown in Figure 11, are typically medium to dark grey, sparsely to moderately fossiliferous, massive, well-indurated micrite. They are generally thicker-bedded than the shallower-water facies of the West Spring Creek, but, on the whole, thinner than the subtidal facies of the underlying Kindblade Formation. The fossils were better preserved, commonly in life position because the sediments were deposited below wave base; they consisted principally of trilobites, gastropods, pelecypods, and brachiopods.

Upper subtidal zones and lower intertidal zones generally consist of oolite shoals and their associated lithofacies, such as packstones and grainstones of fossil and oolite debris seaward of the shoals. Packstones and grainstones of slightly better-preserved fossils, ooids, and grapestones are emplaced leeward of shoals. Figure 12 shows a typical oolite bed, most of which are one to two feet thick, well-indurated, and commonly bounded above and below by shaly strata. Figure 13 is a typical sample of oolite with ooids enclosed in micritic envelopes; also

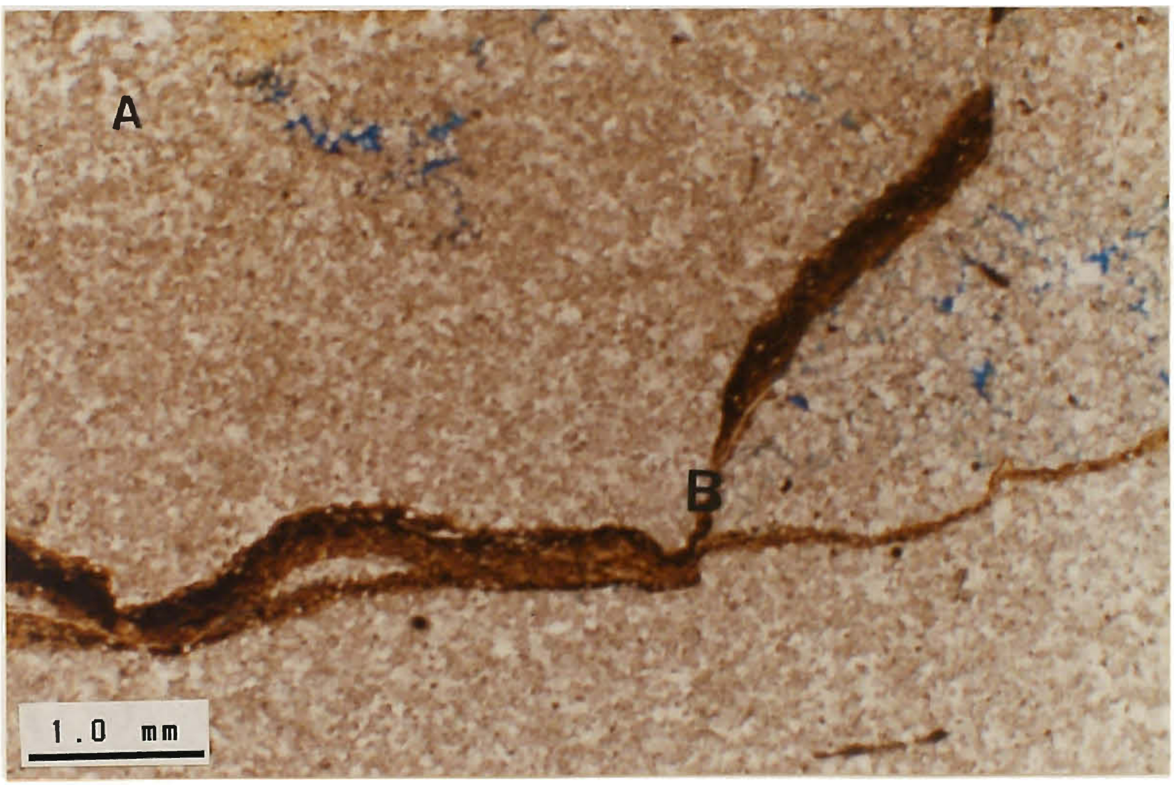


Figure 11. Photomicrograph of subtidal facies, showing a dense micrite fabric partially altered to microspar (A) with a hematitic stylolite (B).

Figure 12. Photograph, outcrop of an oolite shoal facies, representative of upper subtidal to lower intertidal facies.

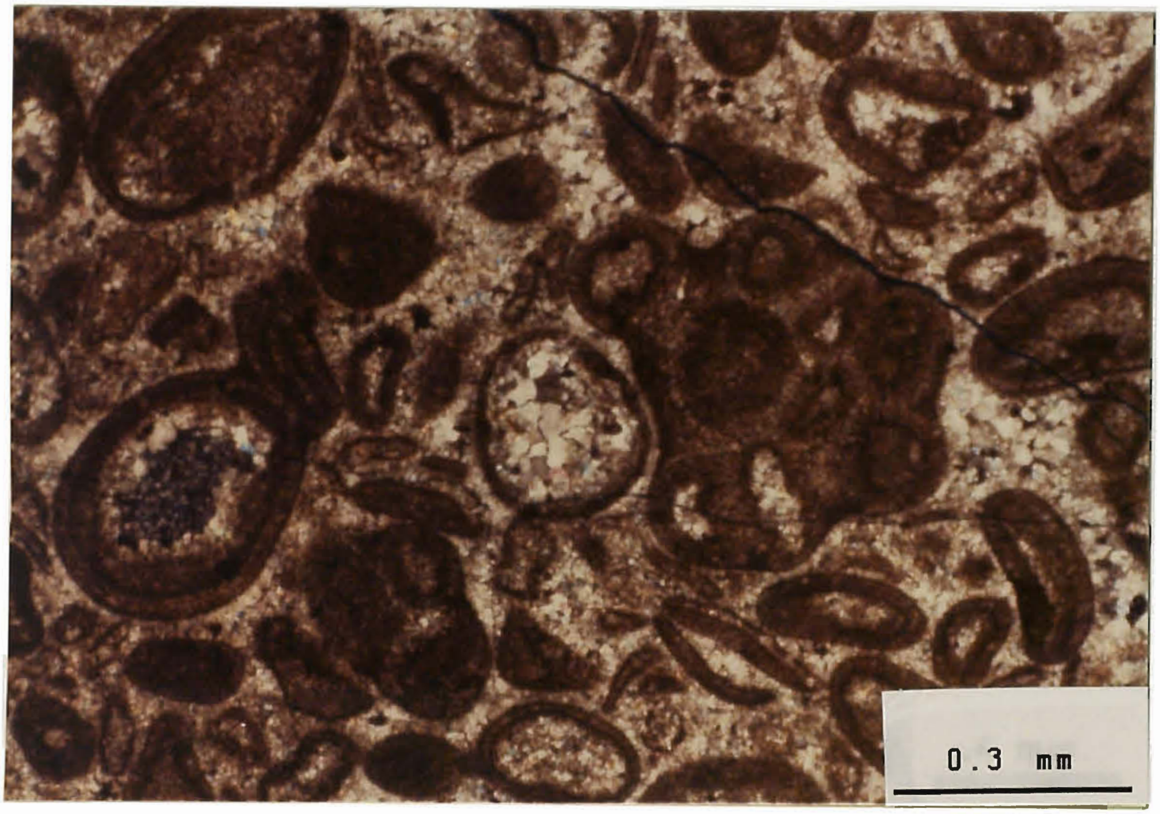


Figure 13. Photomicrograph of ooids, peloids, and grapestones, some with micritic envelopes.

included are peloids and grapestones. This sample is most probably from the shoreward side of the shoal.

Intertidal deposits generally are thinner-bedded than those of deeper water and many show evidence of a stronger terrestrial influence. Influx of clays resulted in shaly limestones or marls (Figure 14) with a dearth of fauna, as the terrestrial sediments made an environment that tended to suffocate marine life. Very mature sandstone grains were common detritus. Many fossil fragments were washed and broken by wave action, as illustrated in Figure 15. In restricted areas such as lagoons, sediments generally were dark grey, bioturbated (Figure 16), with sparse syneresis cracks and thin laminae of sand grains. Intertidal to upper intertidal zones are characterized by algal growths, or stromatolites; these ancient structures are abundant in much of the Arbuckle Group. Although the most spectacular ones are in the Cool Creek Formation, the West Spring Creek has an abundance of stromatolites, some of which have not been described. Figures 17 through 19 show representative stromatolite structures. They range from large four- to six-foot solitary hemispheroids to small, one-half- to two-inch laterally-linked hemispheroids (nomenclature from Ansley and Chase, 1974). Some of the smaller ones were not discovered until the rocks were slabbed.

Supratidal facies, perhaps best represented by evaporites, are uncommon, and none were observed in this study. Many evaporites that have been exposed to surface

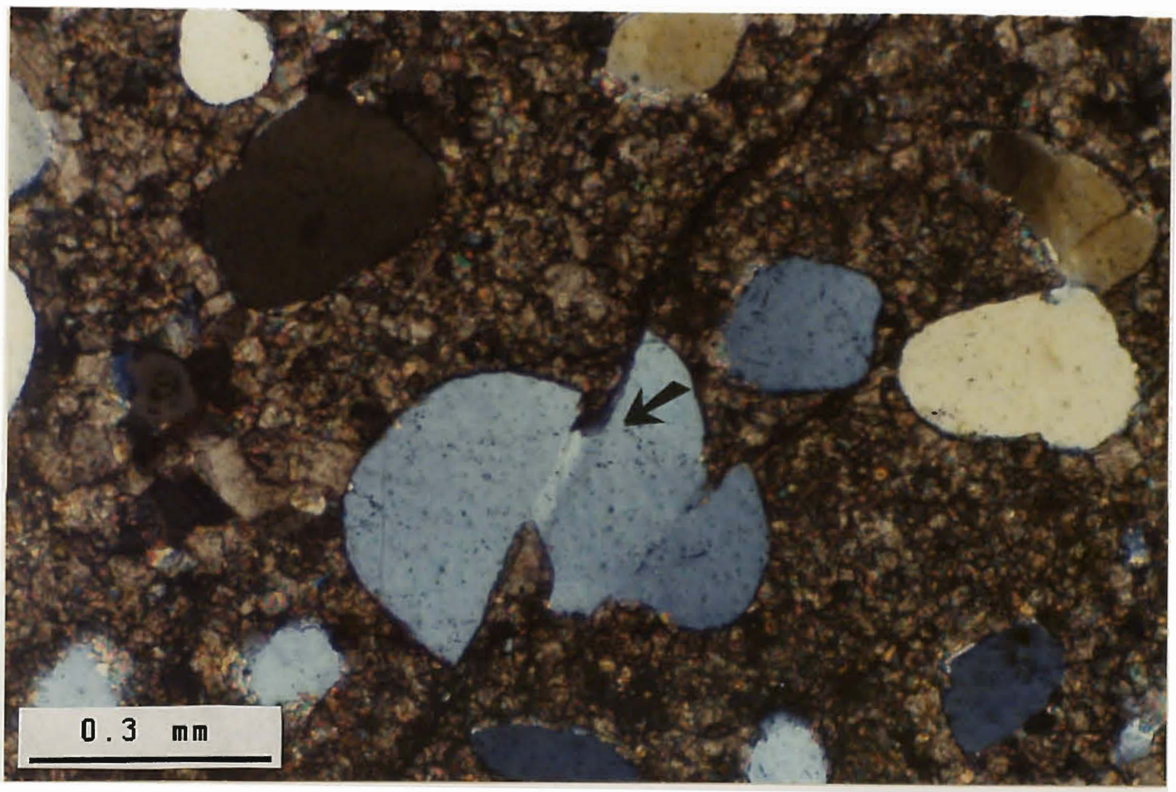


Figure 14. Photomicrograph of sand grains in an intertidal marl. Note fracture and displacement of quartz grain (arrow).

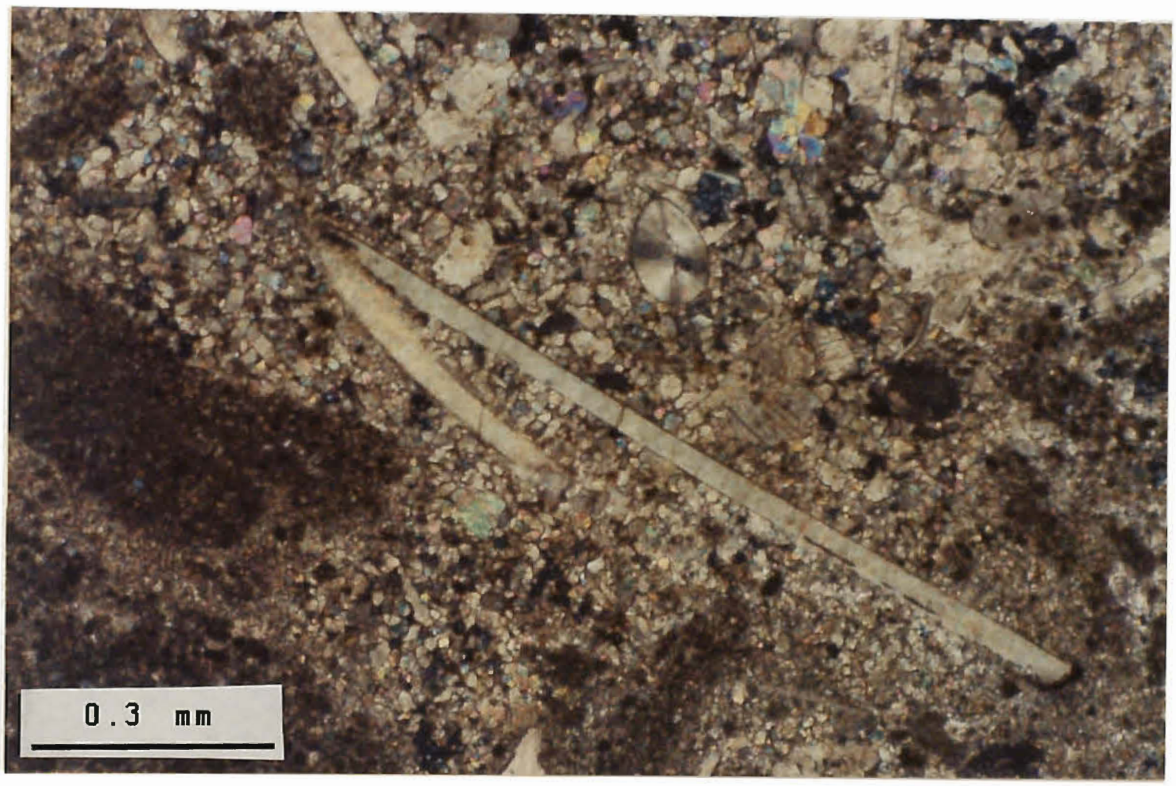


Figure 15. Photomicrograph of bioclastic wackestone, common in the intertidal zone. Central elongate fossil is a trilobite fragment.

Figure 16. Hand-sample photograph of burrowed, dark grey lagoonal deposits with a weathered surface.

Figure 17. Photograph of large stromatolite classed as a solitary hemispheroid. Note glove for scale.

Figure 18. Photograph, laterally-linked hemispheroid (LLH) stromatolite. Note pen at arrow for scale.

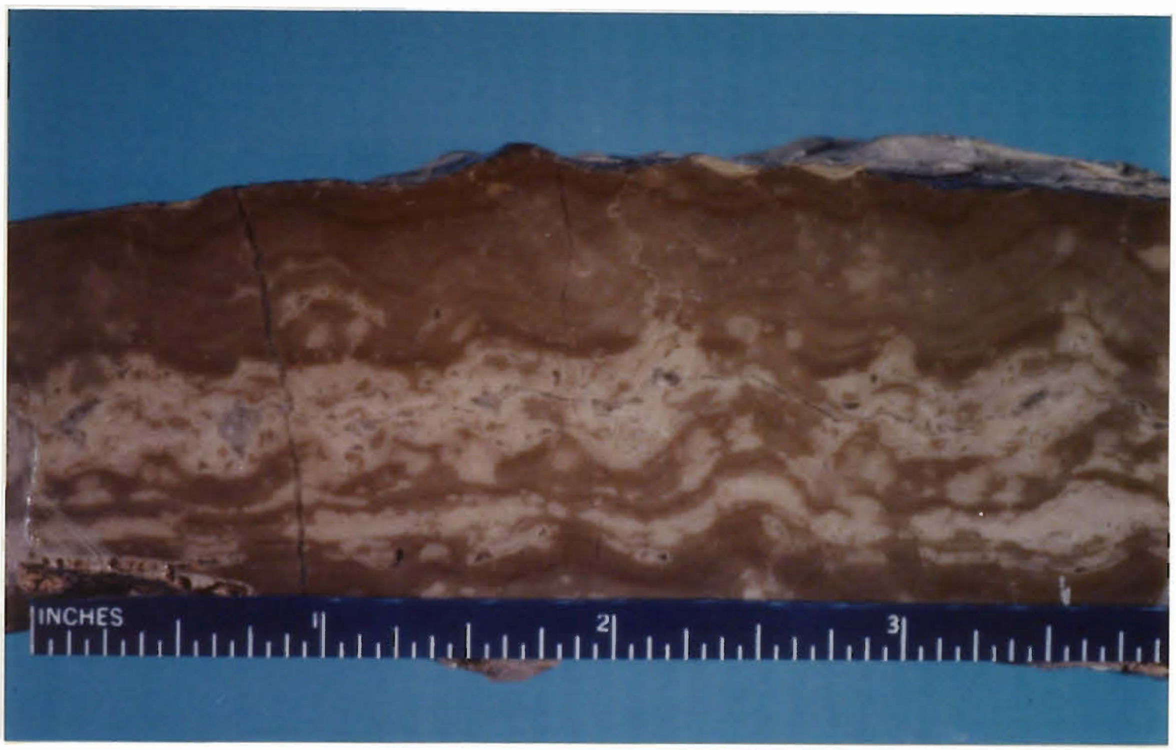


Figure 19. LLH stromatolite approximately two inches high.

erosion and meteoric waters are altered neomorphically or are replaced by other diagenetic minerals such as calcite, but not any of this was observed. Lynch (1991, p.34), reported that "evaporites are encountered far more frequently in the literature (Reed, 1957; Latham, 1970; Gatewood, 1978; St. John and Eby, 1978; Beales and Hardy, 1980; Ragland and Donovan, 1985) than in either the outcrop or subsurface." Some mudstones with irregular laminae closely resembling varves are mostly likely upper intertidal/supratidal facies deposited in tidal flats with seasonal marine-input fluctuations (Figure 9), although no halite pseudomorphs were observed.

Examples of all of these facies were collected from the red-bed sequence selected for more extensive investigation. Observations at various sites in the Arbuckle Group of similar features, such as the individual depositional facies types and the shallowing-upward cycles, have been documented in earlier studies by Musselman (1989), Lynch (1989, 1991), Wilson (1991), and Al Shaieb (1988).

Diagenesis

The diagenesis of carbonate rocks is most difficult to determine, and the degree of difficulty increases with the age of the rocks. Due to their soluble nature, events of dissolution and precipitation frequently obscure or obliterate earlier events. As a result, the paragenetic sequence presented here is limited and general.

Early marine phreatic calcite is visible in most of the samples. Tight, unfossiliferous micrites show some evidence of neomorphic replacement by microspar. Figure 20 is a biomicrite from an intertidal zone showing a micritic geopetal structure and early, pore-lining calcite. As diagenesis continued, marine phreatic microspar, dolomite, and meteoric sparry calcite formed within this gastropod. The latest event in this photo is fine-grained chert replacement of the sparry calcite.

The microspar in Figure 21 replaced primary micrite in a random fashion. Figure 22 illustrates replacement microspar in a fabric-controlled example. Little isopachous calcite cement is in evidence (as seen in Figure 20).

Figure 23 shows evidence of at least two episodes of dolomite precipitation. The center of the matrix crystals appear dirty and seem generally to be composed of fine grained rhombic to hypidiotopic crystals. Dolomite of this type is interpreted to be primary syndepositional or eogenetic in origin (Lynch, 1991). The outer zones of the larger crystal in the center are later, idiotopic E cements, deposited during early burial. Also significant in this photomicrograph is evidence of replacement of the core of this zoned dolomite rhomb by calcite. This may have been related to exposure to meteoric waters.

Also associated with early diagenesis are small pyrite nodules, common within fossils filled with calcite

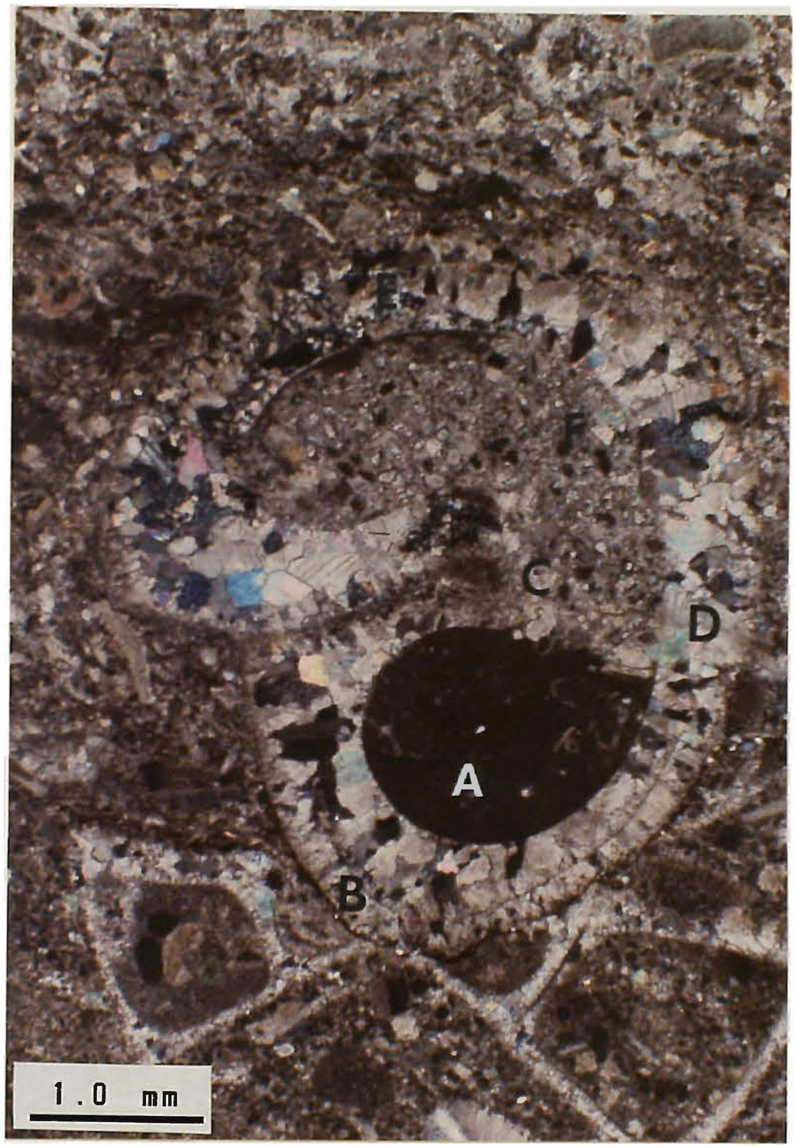


Figure 20. Photomicrograph of a diagenetically altered gastropod. Early geopetal structure of dense micrite and pore-lining calcite (A and B, respectively) initiated the diagenesis, followed by marine phreatic microspar and dolomite (C and F). Final events were precipitation of fine-grained chert and meteoric sparry calcite (E and D).

Figure 21. Photomicrograph of primary micrite (W) replaced by microspar (X). Fossil fragments are trilobites. Also shown are a micritic rip-up clast (Y) and meteoric sparry calcite (Z).

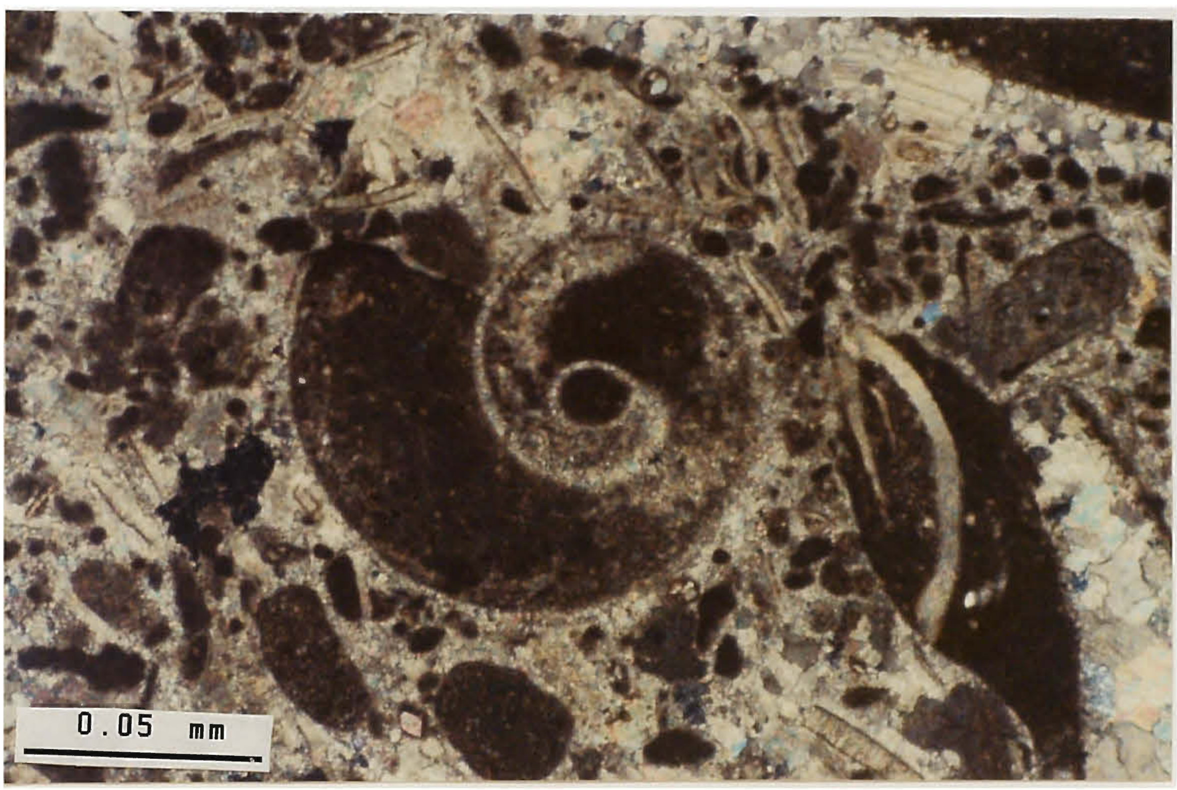


Figure 22. Fabric-controlled replacement of micrite matrix by microspar, in bioclastic grainstone.

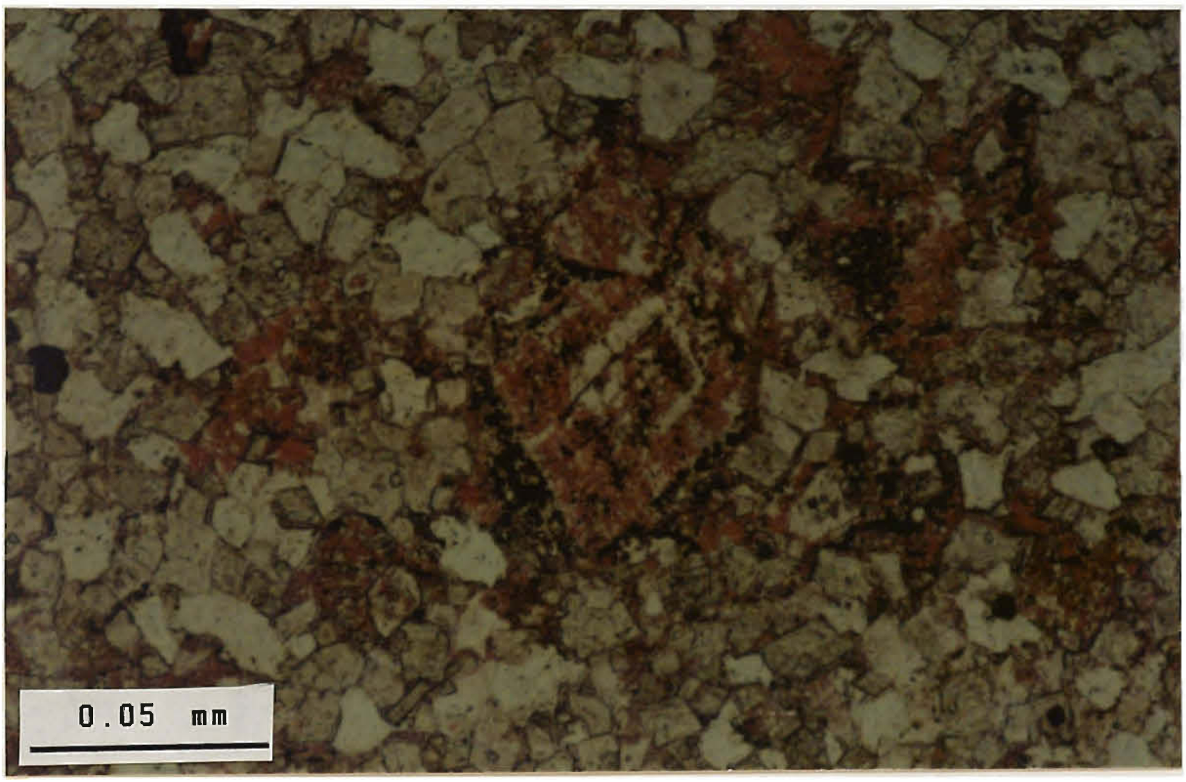


Figure 23. Photomicrograph of zoned dolomite in a matrix of hypidiotopic dolomite. Multiple episodes of dolomitization are represented. Alizarin-red staining indicates dedolomitization.

spar or chalcedony, as shown in Figure 24. Another ferrous mineral is ferroan dolomite, or ankerite, which has been identified by X-ray diffraction (Figure 25). This ordinarily weathers to a yellowish-brown tinge as oxidation results in alteration to limonite on exposed surfaces.

Chalcedony and chert are related to eogenic or mesogenic stages (early to midway of burial time). As burial progresses, formation waters become increasingly acidic, creating the proper climate for silica precipitation and calcite dissolution.

Cochran and Elmore (1987) reported that burial temperatures of the Arbuckle Group probably never exceeded 100^{o} C, but fluid inclusion studies at Oklahoma State University indicate that temperatures of thermal dolomite precipitation were greater than 130^{o} c (Al Shaieb, 1994). These elevated temperatures were probably a result of heated subsurface brines or basinal fluids that ascended through fractures or faults. This form is common in the core examined in this study as well as surface samples. Figures 26 and 27 are photomicrographs of thermal dolomite from core samples.

Although some meteoric calcite formed during early burial, fractures filled with blocky calcite of the meteoric phreatic type similar to that in Figure 28 may be related to uplift and folding of the Arbuckle during Pennsylvanian time. Pressure seams developed in conjunction with burial and/or orogeny resulted in calcium-

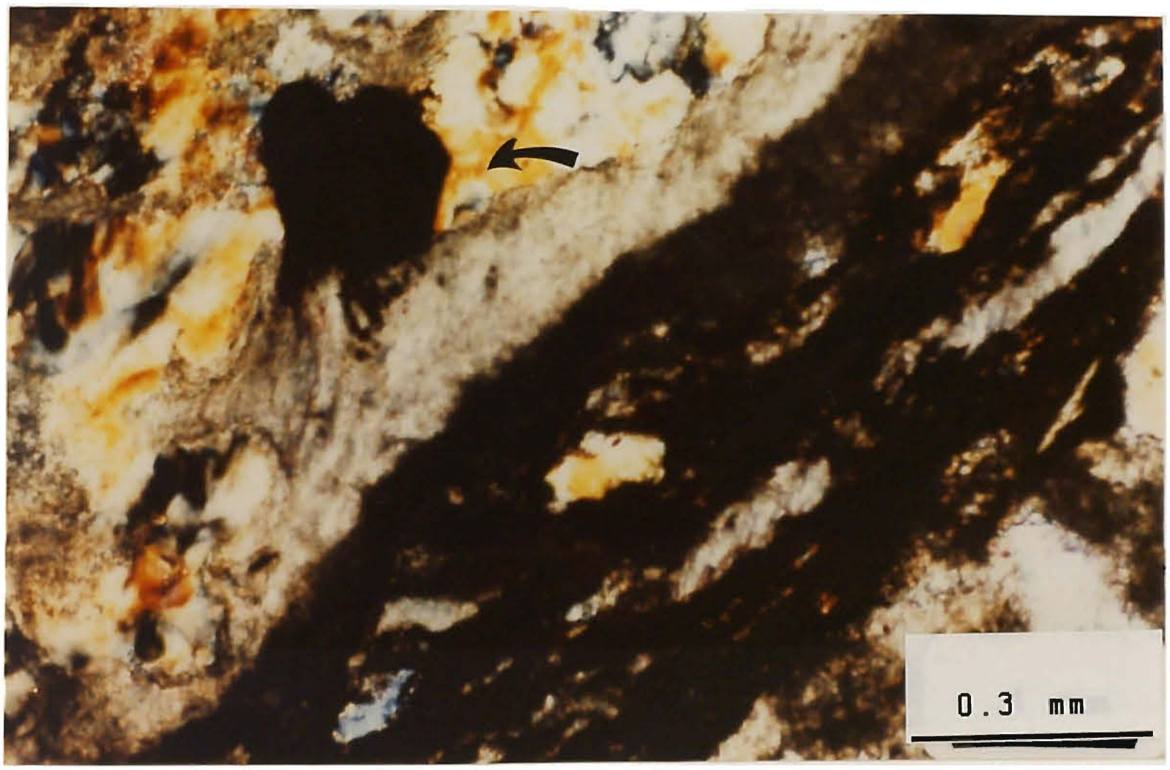


Figure 24. A pyrite nodule (arrow) surrounded by chalcedony in the core of a brachiopod: interpreted as an early diagenetic feature.

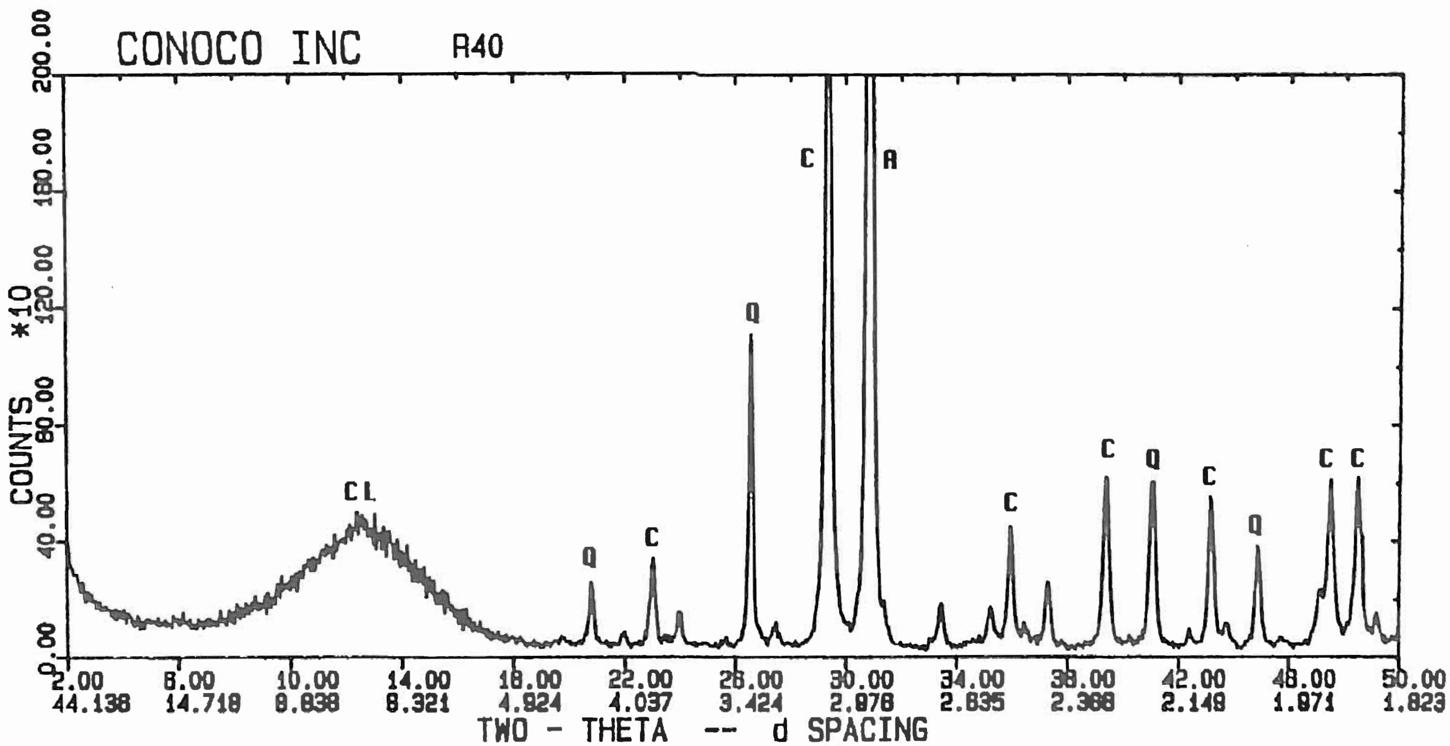


Figure 25. X-ray diffractometry curve featuring ankerite. Key: C=calcite, Q=quartz, A=ankerite, CL=clays.

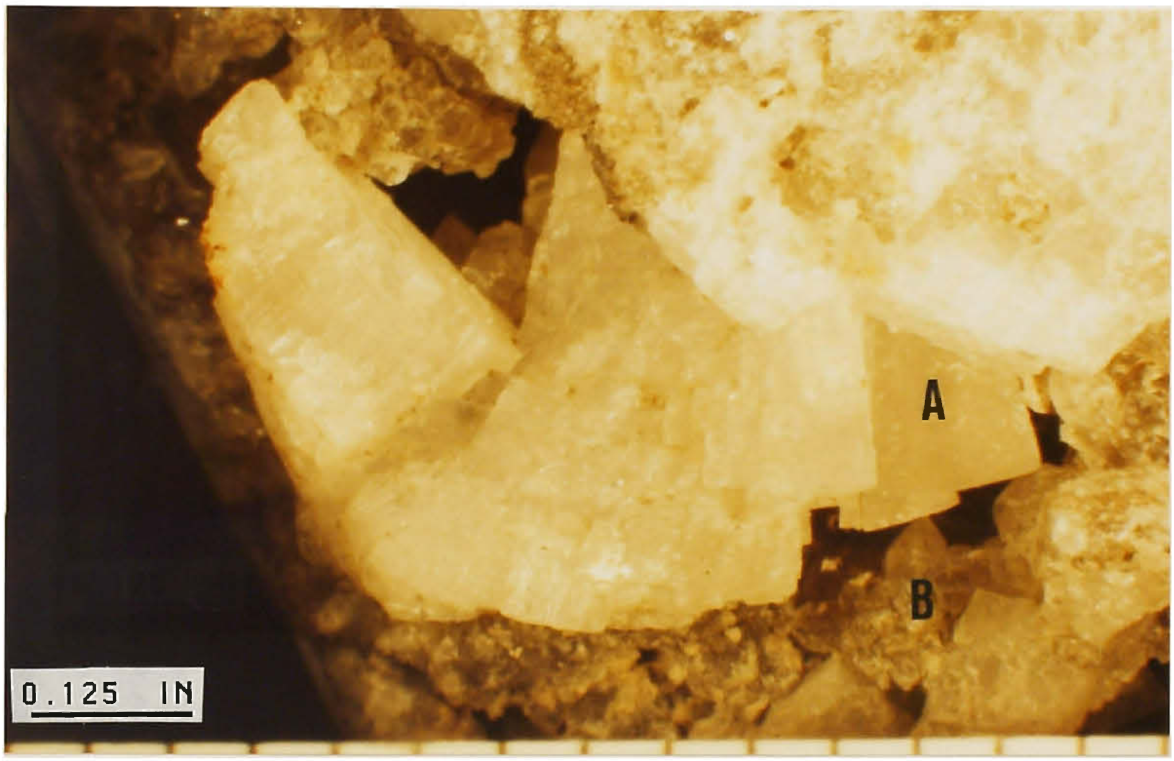


Figure 26. Thermal dolomite (A) in core. Note quartz crystals (B). Photomicrograph was taken through a binocular petrographic microscope.

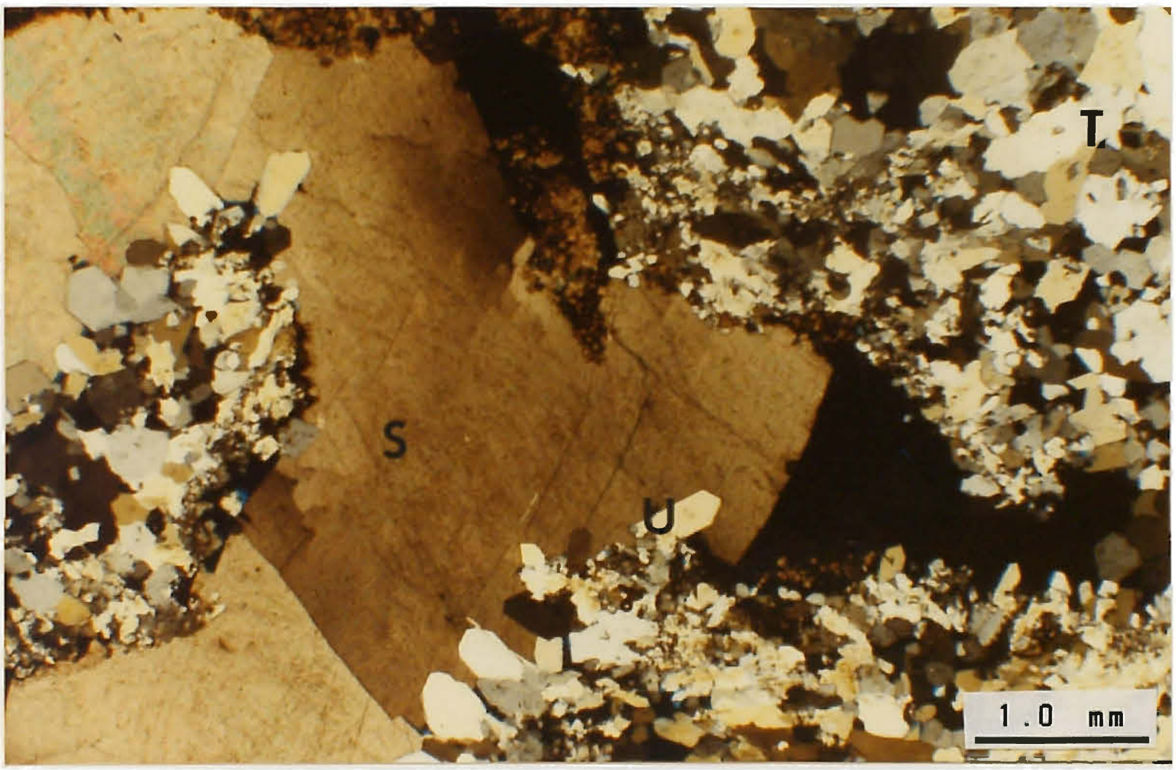


Figure 27. Photomicrograph of thermal dolomite (S), by a polarizing petrographic microscope. Also shown are anhedral silica cement (T) and euhedral quartz crystals (U).

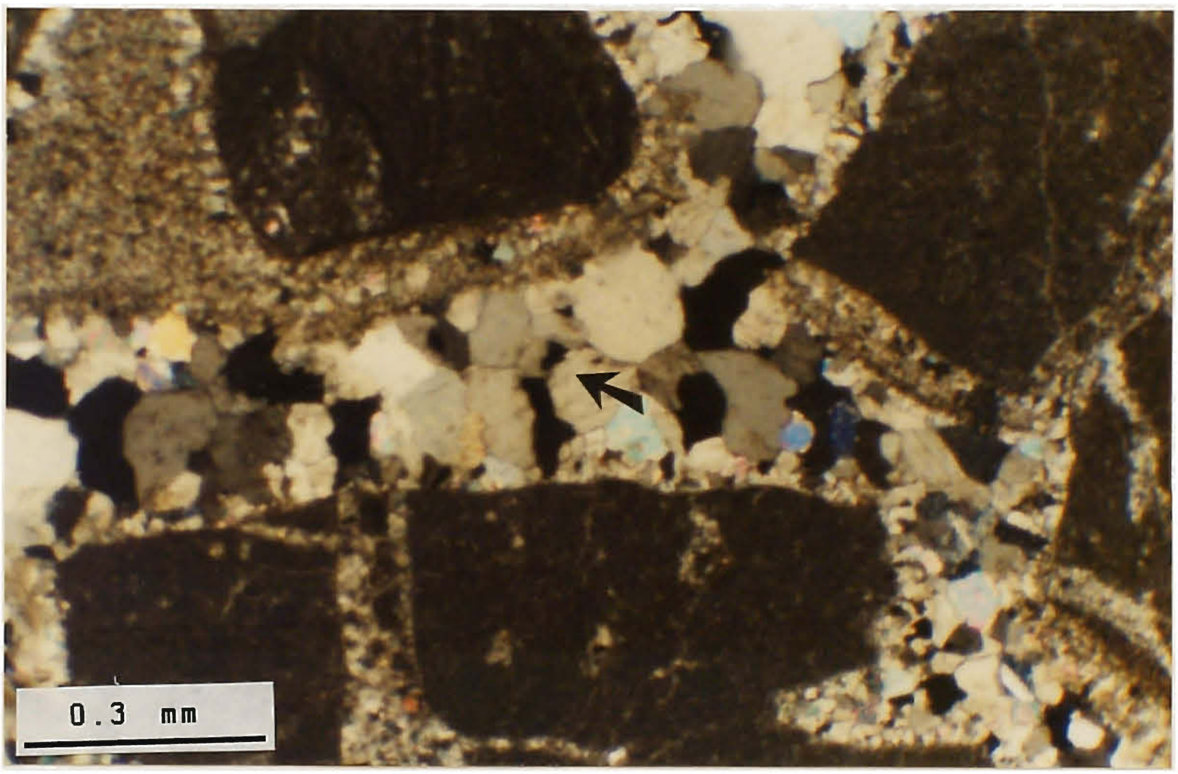


Figure 28. Photomicrograph of fractures filled by blocky calcite (arrow), associated with meteoric phreatic zones.

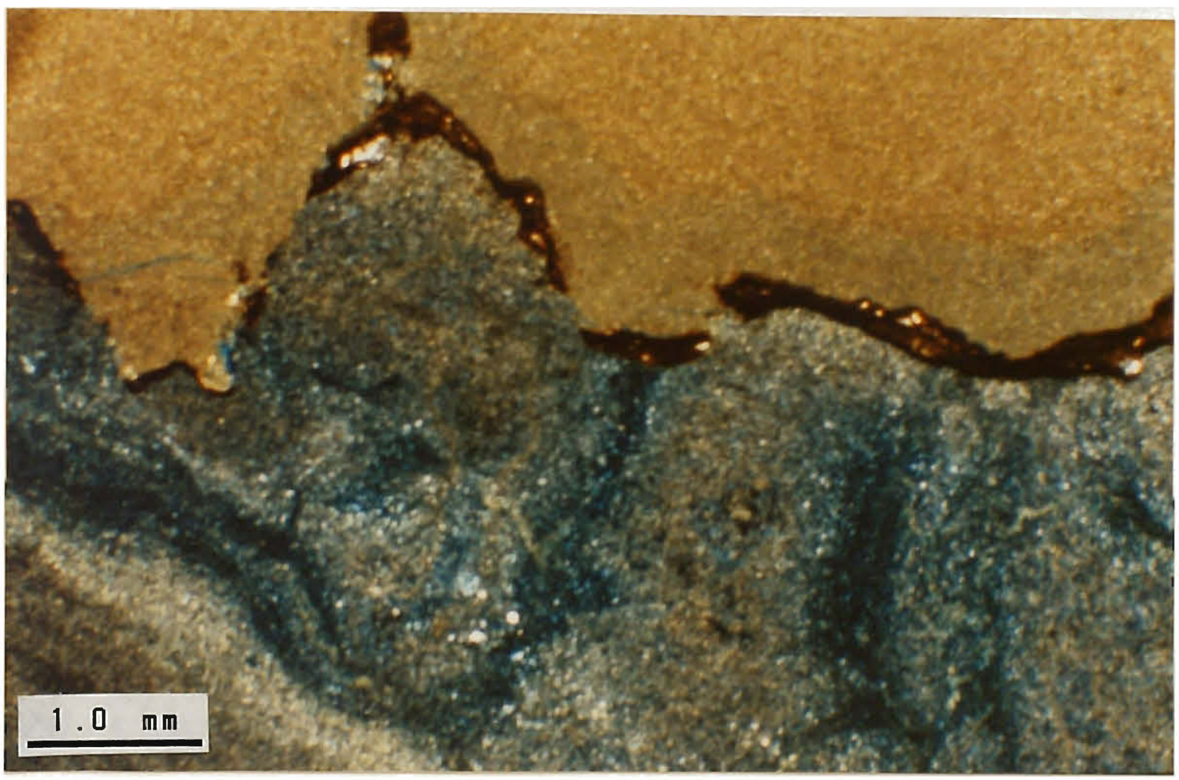


Figure 29. Photomicrograph of a stylolite along which are concentrations of hematite. Note stylolite has acted as a seal, preventing dissolution of micrite above it.

and iron-rich solutions that infiltrated along clay seams and microstylolites. Calcite precipitated, often as a dedolomitization process; hematite was also precipitated. (Figure 29). The paragenetic sequence summarizing this limited history is illustrated in Figure 30. Further thin-section analyses probably would reveal more complexities of the paragenetic sequence, but such analyses are beyond the scope of this paper.

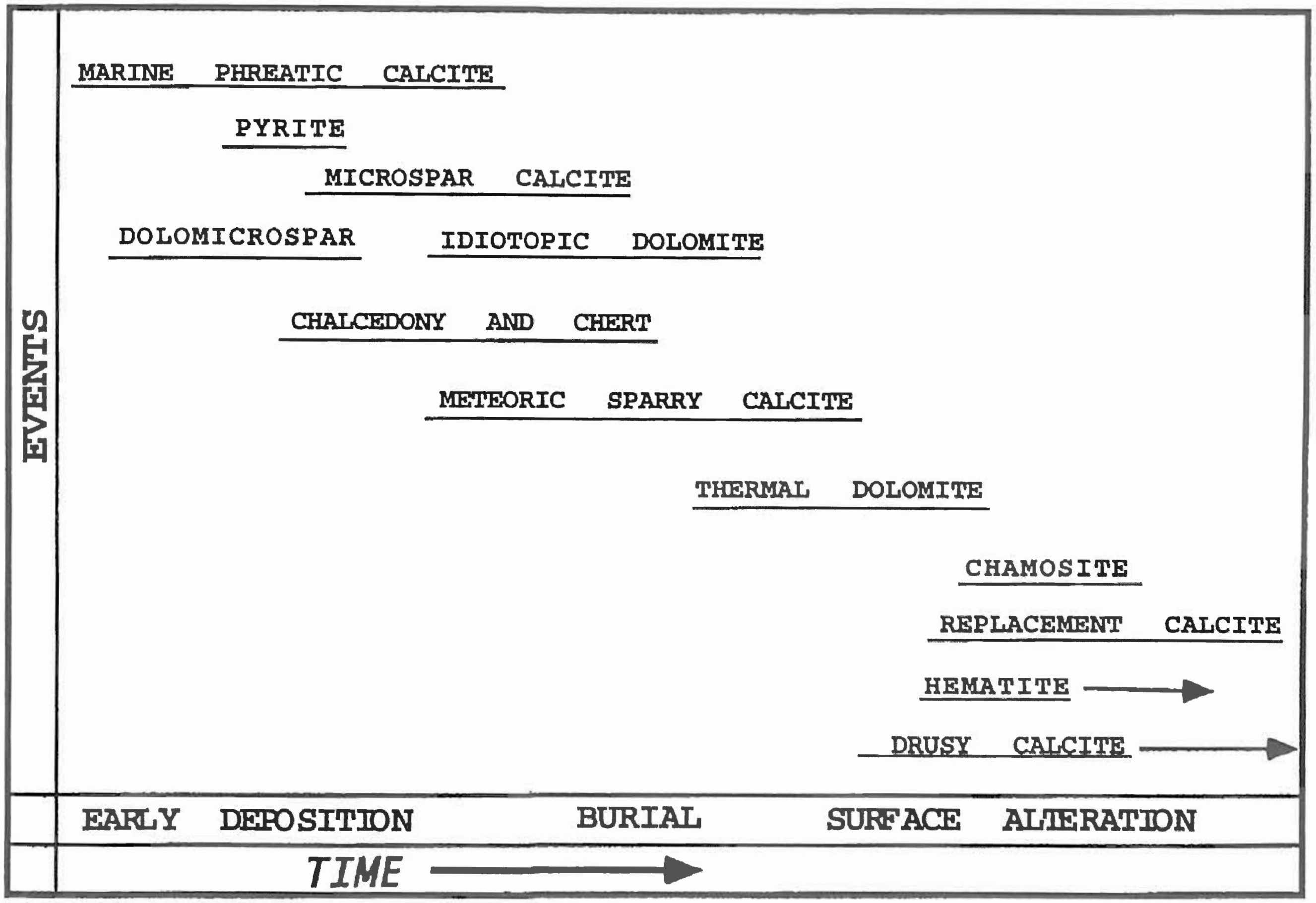


Figure 30. Generalized paragenetic sequence of the West Spring Creek.

CHAPTER IV

PALEOKARST IN RED-BED SEQUENCES

General Description

Interbedded throughout the middle zone of the West Spring Creek Formation are anomalous dark red, red, pink, and lavender mudstones, shaly limestones (marls), and limy shales. The outcrop shown in Figure 31 shows some indication of the variation in color. The uppermost of these red-bed sequences (77.6 feet thick) was studied in detail, in order to investigate the possibility that these variations in color represent sub-aerial exposure and subsequent erosion and karstification. These hiati would have been precursors to the pre-Simpson unconformity, during the formation of which erosion truncated the Arbuckle and karst developed.

A descriptive log using Fay's 1969 measured-section bed-numbering system as locators to correspond to the sample numbers for this study is present in Appendix A. This author's descriptions are from outcrop, hand samples, thin section analysis, and X-ray diffractometry. The most frequently used rock-classification nomenclature is Dunham's system (1962), as it seems better fitted to descriptions of hand samples, but Folkian terms do tend to

Figure 31. Outcrop of the upper red-bed sequence on Interstate 35, the top of which is 287 feet below the top of the Arbuckle.

creep in insidiously, even in this description of an outcrop. A sketch from photographs of the upper red-bed sequence is in Plate 1. An "s" after the bed number indicates a sandstone; "o" indicates an oolite bed, "r" indicates a red bed, and "b" indicates a breccia.

Karstic Features

Paleokarstic features in the West Spring Creek Formation are various types of karstic breccia, vugs, solution-enlarged channels, and sediment infill of dissolution features. Terrestrial deposits in these red-beds are rare and confined to the capping sandstone and minor sandstone laminae within limestone beds. These sands may have been windblown or washed from land after times of heavy rainfall. All other deposits were near-shore marine carbonates or karstic debris. Flat-pebble conglomerates or intraformational conglomerates were observed locally, usually as thin (one-half inch to three inches) intervals within beds of mudstone. These seem to have been associated with storm surges and probably formed when partially lithified sediments were loosened or ripped up from the sea floor, transported a short distance, and deposited. A typical example of these conglomerates is shown in Figure 32. The clasts are flat, elongated, and have a preferred alignment "parallel" to bedding. They are mostly poorly sorted, but do not show extreme variations in size.

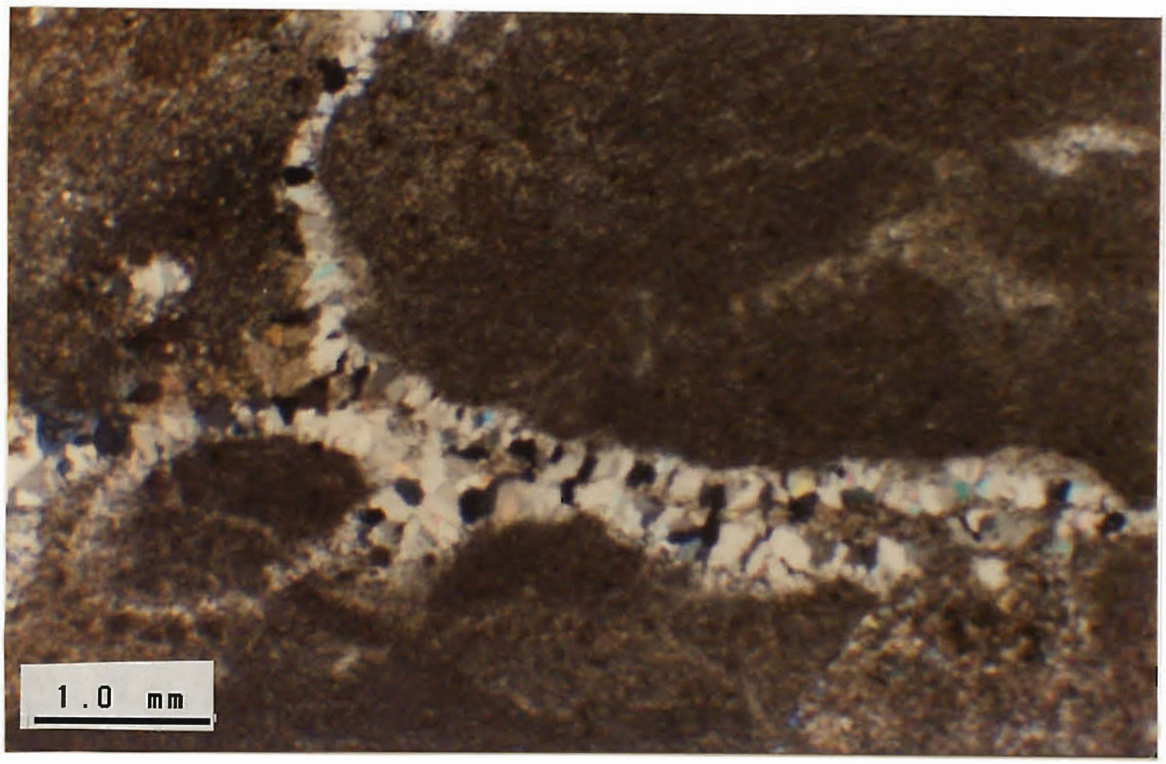


Figure 32. Photomicrograph of a typical flat-pebble conglomerate.

Karstic-breccia clasts, which are frequently more rounded than angular, are described well by Charles Kerans (1989) from the Ellenburger karst and in Ijirigho's and Schreiber's 1986 paper. Collapse breccias may have the form of "tabular bedding-parallel shapes or vertical cylindrical to ellipsoidal shapes" (Kerans, 1989). Most undergo little or no transport, and may contain in their matrix any constituents as old as or older than karstification. Figure 33, which incorporates the nomenclature of Kerans' and Ijirigho's and Schreiber's work with that of Lynch's (1987), illustrates the terms used in this paper and the characteristics of each type of karstic breccia.

For the most part, breccias within the uppermost red-bed sequence are what have been called depositional karst by Choquette and James (1988). The primary difference between them and other karstic breccia is that breccias in the red-bed sequence do not cut across bed boundaries. The chaotic arrangement of clasts within these breccias (Figures 34 and 35) differentiates them from simple storm deposits such as flat pebble conglomerates, but they may well be related to periods of heavy rainfall upon the karstic terrain. Crackle and microdil breccias, loosened by meteoric water flow through solution-enlarged fractures, faults, and bedding planes, can calve from the cave roofs and walls and be deposited in the lime muds of the cave floors. If there were sufficient water flow across these

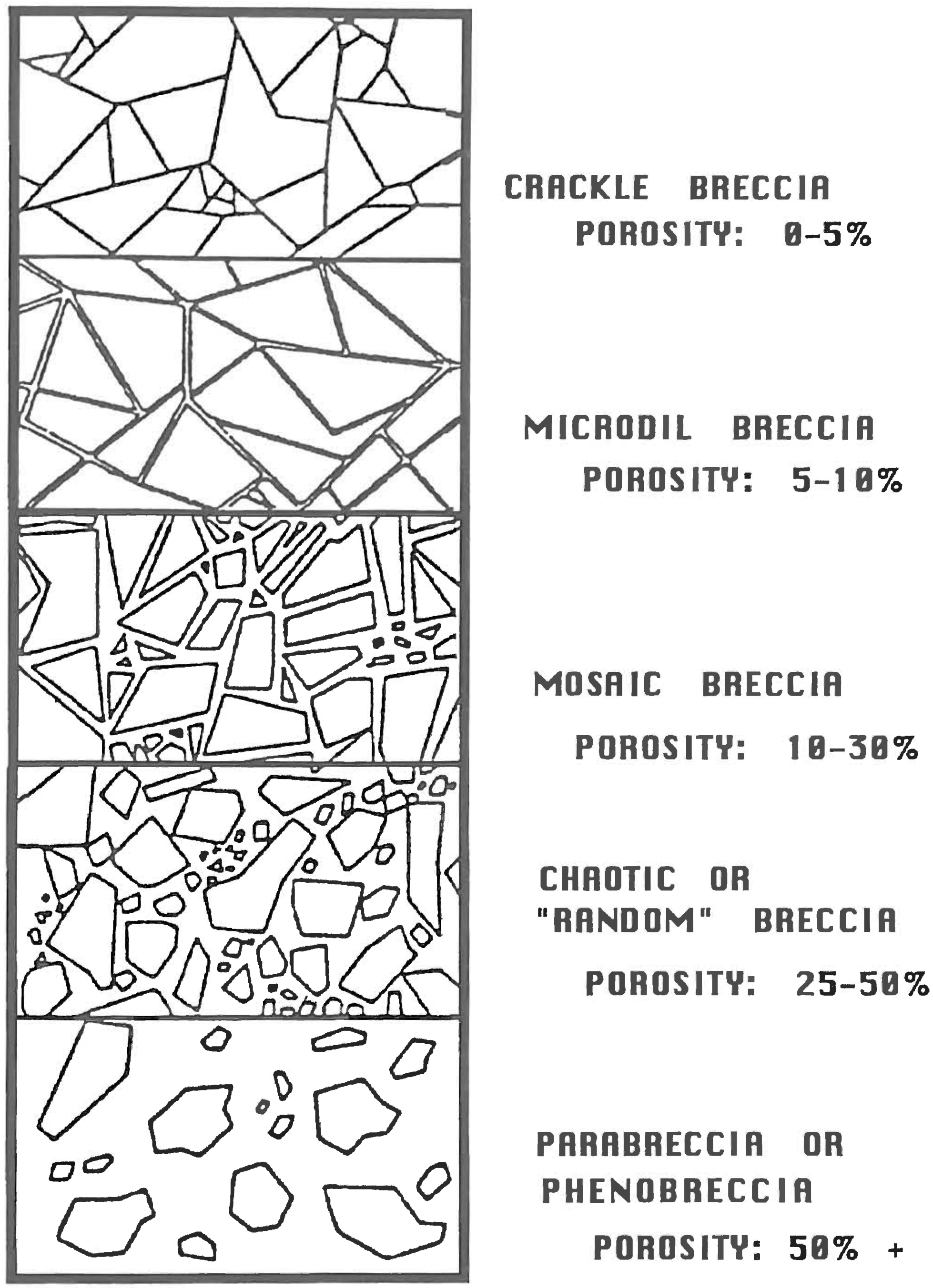


Figure 33. Cartoon of breccias related to karst (Modified after Ijirigho and Schreiber, 1986; and Lynch, 1987).

Figure 34. Photograph, hand-sample of collapse breccia.

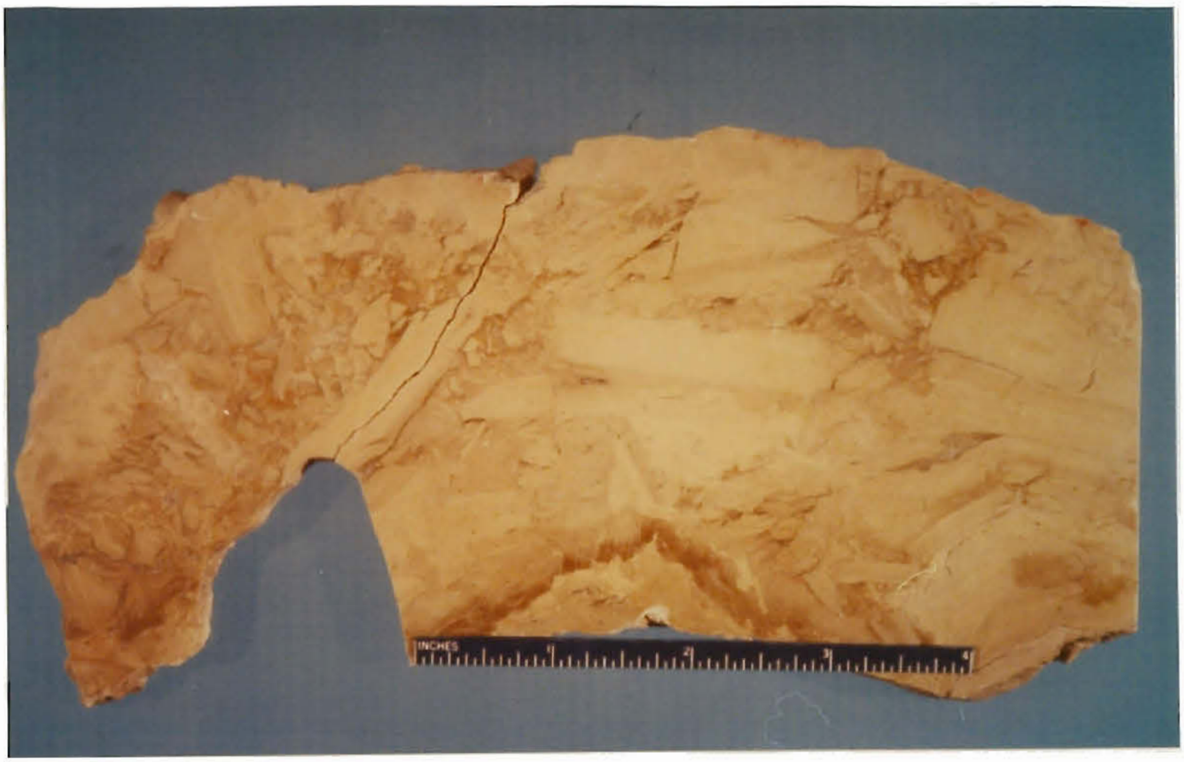


Figure 35. Photograph, hand-sample example of chaotic texture of collapse breccia.

cave-floor deposits, some transport could occur. The significance of collapse and cavern-fill parabreccias is that they are in fact constrained by bed boundaries and are overlain by Arbuckle carbonate rocks. They also do not appear to contain any sediments from rocks of a younger age. For these two reasons the breccias most likely formed during deposition of the Arbuckle.

Another type of deposit within the red beds is a mottled red and grey-green micrite, such as Sample 11, interpreted to have been a terra rosa deposit (Figure 36). It is overlain by marls (Figure 37) and karstic breccias (Figures 38 and 39).

Thin-section analysis revealed no constituents that could be construed to be younger than Arbuckle rocks. Terrestrial constituents consisted of very fine to fine-grained, well rounded, well sorted sand grains, with few microlites or vacuoles (Figure 40). These appeared as discrete grains within the mudstones and algal boundstones and as rare sandstone beds. Their texture and morphology suggest a granitic source. The absence of any younger sediments also is a compelling argument for placing the oldest paleokarst within the time of deposition of the Arbuckle.

Given that certain favorable conditions exist, such as sufficient rainfall, ground-water circulation, and undersaturated conditions, subaerial exposure of soluble deposits such as the Arbuckle limestones would logically

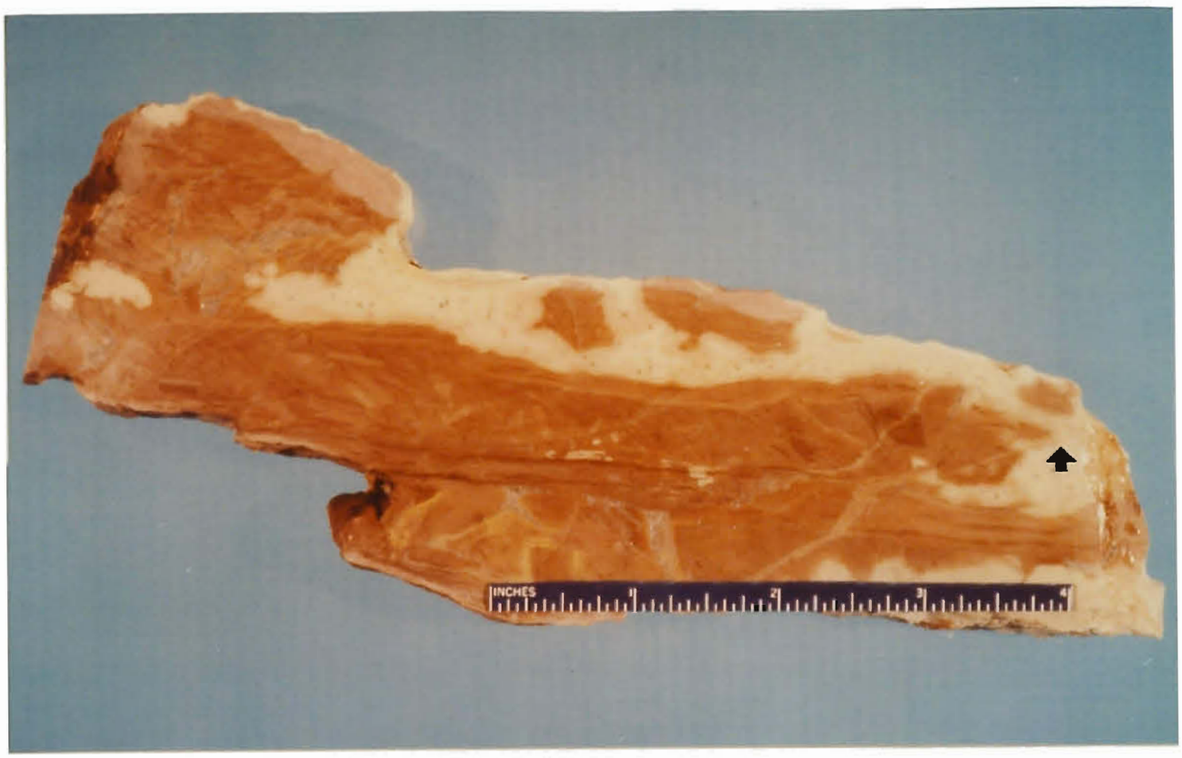


Figure 36. Red and grey mottled mudstone interpreted as a terra rosa deposit. Arrow shows "up" orientation relative to bedding. Note lamination parallel to bedding.

Figure 37. Shaly limestone or marl characteristic of deposits overlying karstic features within the red-bed sequence.

Figure 38. Weathered surface of collapse breccia from upper red-bed sequence.

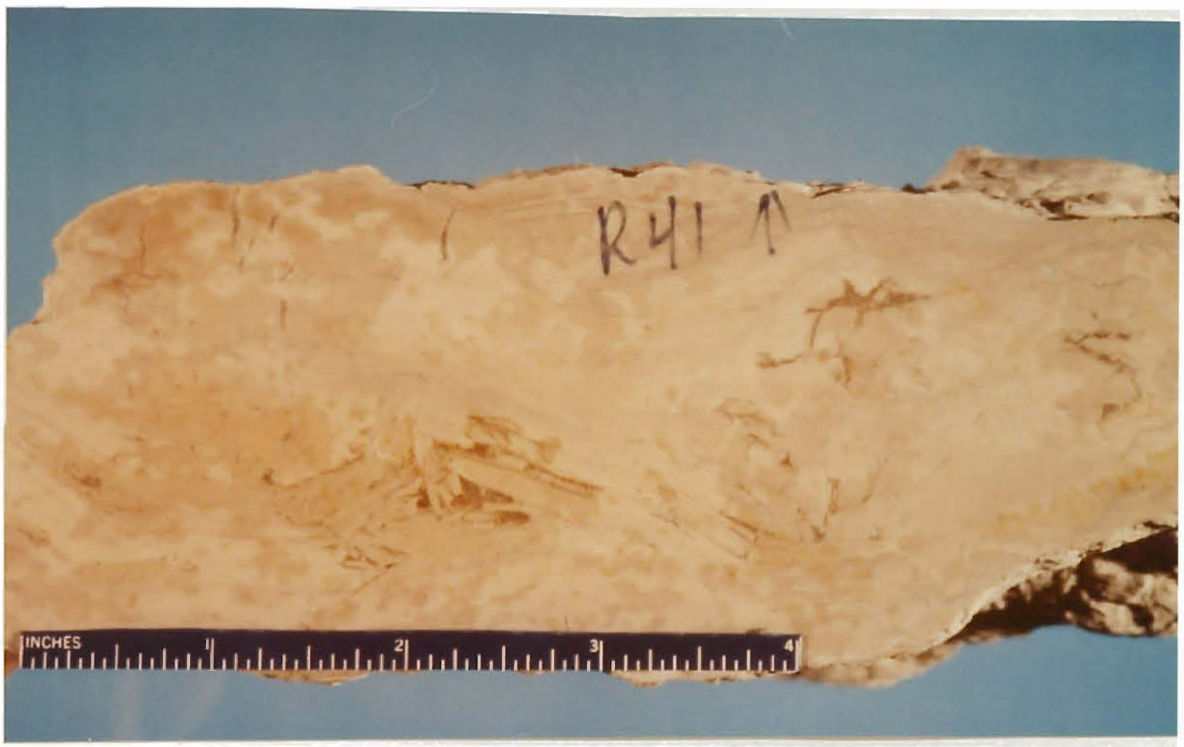


Figure 39. Mud-dominated parabreccia associated with cave-floor facies.

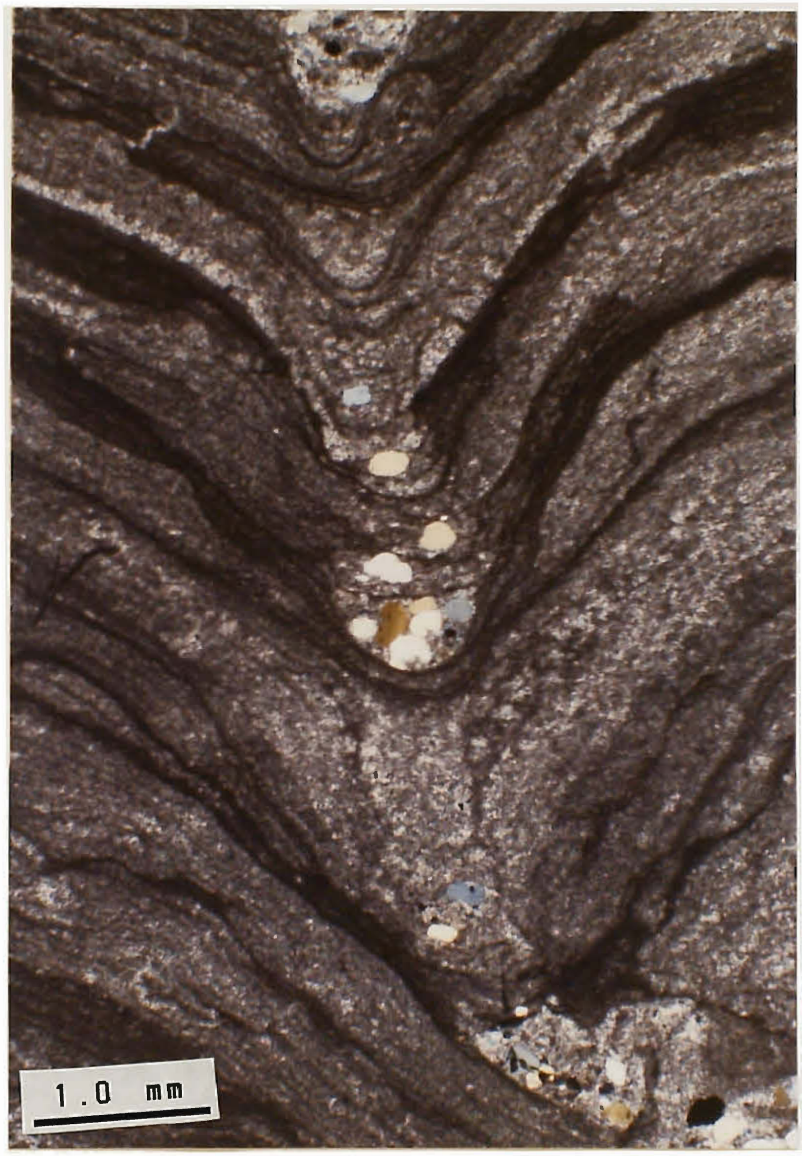


Figure 40. Sand grains typical of West Spring Creek, trapped within stromatolite mounds.

result in karstification. Orogenic processes need not be present, as we see in the Florida peninsula today, nor does terrestrial relief necessarily need be very great. Speleothems, none of which were identified in this study, need not be a significant feature in paleokarst. Kerans (1989) stated "___speleothems are rarely preserved in paleokarst systems, and their absence should not be taken as evidence against karst development." The close proximity of intertidal deposits both above and below these breccias suggests that the caves may have been subjected to transgression and flooding. Kerans (1989) stated that this infilling of caves is common where little terrestrial sediment is available. Figure 41 illustrates the shallowing- upward cycles and spatial relationships of differing depositional environments within the red beds.

Paleokarstic Features in Core

Amoco SHADS #4

In 1987, Amoco Production Company, in testing a new wire-line coring device, the Stratigraphic High-Speed Drilling System, or SHADS, in Rogers County, Oklahoma, cored several wells from near surface to basement. One core, the SHADS #4, was donated to the Oklahoma Geological Survey Core Library in Norman, Oklahoma, in September, 1989. This core is a composite of the four to five wells AMOCO drilled at this site, all 30 to 40 feet apart. There is a total of 3315 feet of core. In an AMOCO report on the

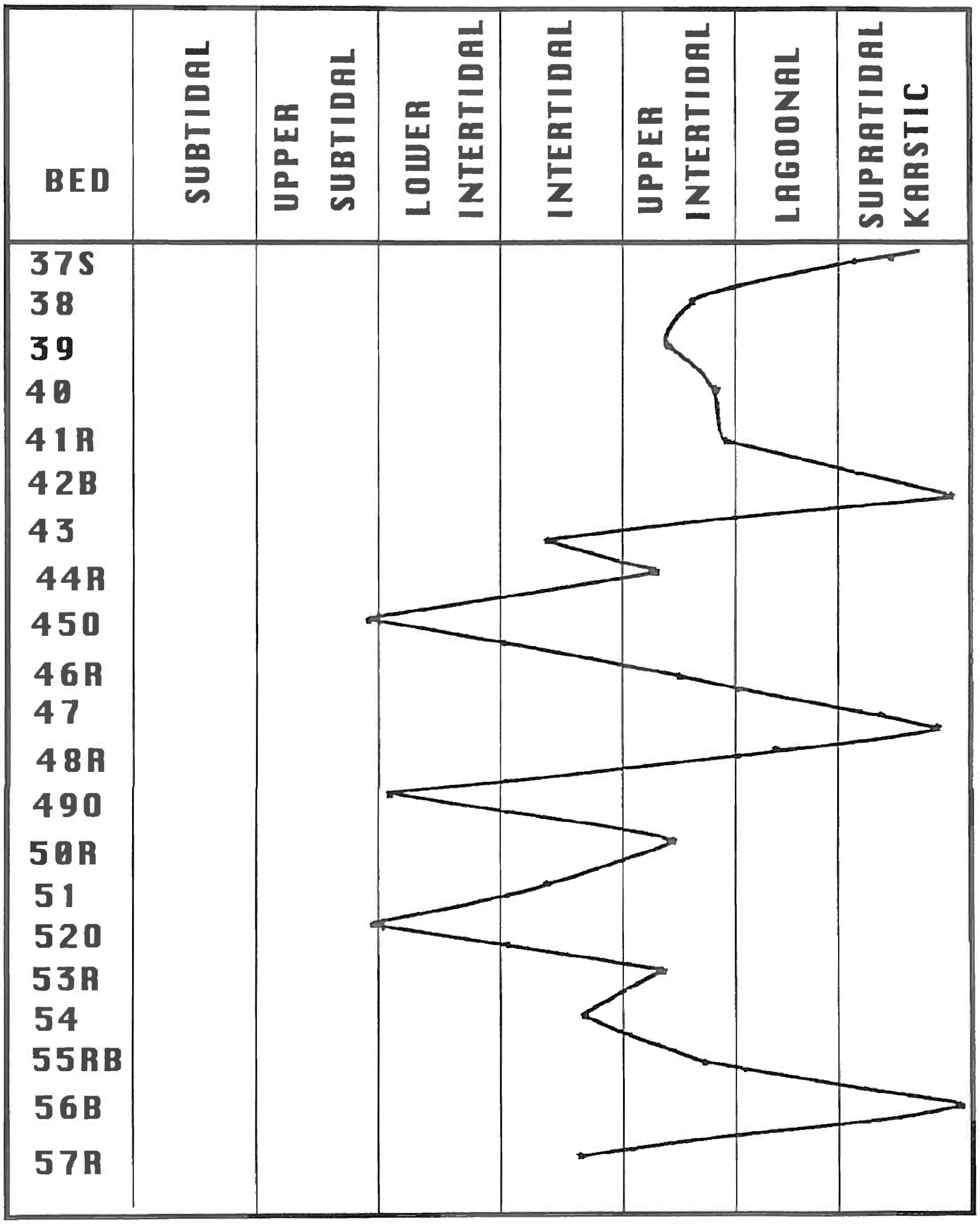


Figure 41. Chart of depositional facies within the red-bed sequence showing fluctuations in the shallowing-upward cycles.

SHADS #1 in 1987 (unpublished), H. H. Hinch indicated that the Arbuckle Group was to be found from 1605 to approximately 2920 feet below ground surface, was overlain unconformably by the Misener Sandstone, and overlay the Spavinaw Granite basement. The SHADS #4 core, according to Charles Mankin of the Oklahoma Geological Survey, probably is one of the most extensive Arbuckle cores in existence, as well as being a complete core of nearly the entire stratigraphic section in northeastern Oklahoma. Part of this core was used as an analog to the surface studies in this thesis.

Just how much Arbuckle was truncated beneath the Arbuckle-Simpson unconformity is unknown, but in a paper presented at the Arbuckle Group Core Workshop (Oklahoma Geological Survey, Norman, Oklahoma, 1991), James Derby identified the top of the Arbuckle to be Cotter and Powell Formations located at a depth of 1607 feet. These two formations correlate quite well with the West Spring Creek, whereas part of the underlying Jefferson City Formation is equivalent to the Kindblade in southern Oklahoma (Figure 1). The core was transported to Oklahoma State University for examination of certain zones, which were identified as soil or brecciated horizons. A petrolog of this core is in Appendix B, and photographs are in Appendix C .

The entire core is dolomite, massive and cherty in numerous zones. Stylolites are ubiquitous. Dissolution vugs are numerous, and many brecciated zones contain crackle and collapse breccias. Oolites, burrowed mudstones, fenestral porosity associated with replaced stromatolite structures, and thin beds and shaly laminae all indicate an intertidal and/or lagoonal depositional environment. No red zones were observed in this core; the entire interval is shades of grey. However, various evidence indicates sub-aerial exposure of these rocks. These are:

1. Caliche
2. Tripoli (degraded chert)
3. Clay stringers or drapes associated with thin shale laminae
4. Karstic breccia

This core provides excellent evidence that the karstification of age-equivalent carbonates was not limited to the Arbuckle Mountains. Lynch (1990) identified similar features in cores. The paleokarst in the Amoco SHADS #4 core differs from paleokarst in the red-bed sequences in that:

1. Only a few crackle breccias were observed.
2. No oxidation of ferrous minerals was noted.
3. Terrestrial constituents (sand grains and clays) were more abundant.
4. Zones of tripoli (weathered chert or siliceous limestone) were observed.

The relative age of karst in this core is inconclusive. No constituents were observed that could be construed as being younger than Arbuckle rocks. The lateral extent of the karst is unknown. Also, because this core is a composite, certain missing sections have been replaced from other cores in the test area. These may be more competent than the original sections, which would obscure the question of the existence of extensive cavern development. The crackle breccia, considered to be related to the cave-roof facies, may be evidence of more extensive cave development than is obvious in the core. Conversely, the numerous stylolites are indicative of deep burial, and the crackle breccia may be no more than intensely fractured rock related to burial pressures. The core is significantly karstic, however, and the soil horizons and caliche also indicate sub-aerial exposure.

CHAPTER V

KARSTIFICATION MODELS

Developmental Stages of Regional Karst

Karst terrain can develop in any soluble rock, such as dolomite, gypsum, halite, or limestone. This discussion is limited to examples and descriptions of limestone and dolomite. All carbonates, limestone included, are more soluble than sandstone and dissolution will occur when one or more of these environmental factors are present:

1. Ground water is undersaturated with respect to calcium and carbonate ions.
2. Ground water discharge\recharge rate is sufficient to maintain undersaturated conditions.
3. Ground water is acidic; as degree of acidity affects the rate of dissolution.
4. Methane or sulfides in gaseous forms (such as those generated by hydrocarbon maturation) are present in quantities sufficient to combine with water vapor and produce acids.
5. Rocks are sufficiently porous and permeable to allow penetration of acids.

Effects of dissolution of carbonates may be limited to enlarged secondary porosity and solution-enlarged fractures and vugs; or it may continue, developing sinkholes and caverns. Speleothems may develop from calcite precipitation.

In arid and semi-arid climates, little karstification occurs. Thin soils, calcrete layers and a few sharp karren form on the surface. In arid zones, little cement forms beneath the surface, occurring most frequently as Mg-calcite and aragonite above the water table, and aragonite and calcite below. More cementation occurs in semi-arid areas than in arid ones, and is usually aragonite and calcite above the water table and only calcite below (Choquette and James, 1988).

In humid, wet climatic environments, rainfall seeps into pores and fractures in limestone, developing dolines (sinkholes) and local rundkarren on the surface. Terra rossa, a term referring to a red, hematitic sediment that fills fractures, vugs, and caverns, is common. In both vadose and phreatic zones, calcite cement is abundant. Cavities, solution-enlarged fractures, and caverns form beneath the surface. Karst development beneath the surface is controlled in large part by fluctuations of the water table. Above the water table is the vadose zone, which is characterized by open vugs, caves, and caverns that receive water through the walls and ceilings and the floors of which often are carved by "underground rivers" during times of heavy rainfall. These rivers often mark the phreatic/vadose interface. The vadose zone has the most extensive speleothem development. Speleothems, the widely varied, beautiful, and probably best-known feature of caves, are results of the reversal of the chemical reaction which originally carved the caves:

$$\begin{array}{c} CaCO_3 + H_2CO_3 \rightleftharpoons 2HCO_3^- + Ca^+ \\ \quad\updownarrow \\ H_2O + CO_2 \end{array}$$

This reaction occurs when rainwater combines with carbon dioxide in the air and soil to form a weak carbonic acid solution, which dissolves limestone. This reaction is reversible, and when the solution becomes saturated with respect to calcium and carbonate ions, calcium carbonate can be deposited as stalagmites, stalactites, cave pearls, curtains, or any other of a myriad of possible forms of speleothems. In the vadose zone, ground water exposed to the air in the cavern can lose some of its carbon dioxide and calcium carbonate can precipitate. Conversely, the phreatic zone, which lies below the water table, is much less likely to contain supersaturated ground water if it is recharged with undersaturated water rapidly enough during each rainfall. This is generally the most active zone of cavern formation, given sufficient water flow. Palmer (1991, p.1) stated "Limestone caves form along ground-water paths of greatest discharge and solutional aggressiveness." He also reported that a maximum rate of wall retreat is in the range of approximately 0.01-0.1 cm/yr.

Lynch (1990) devised a three-stage model of karst development, as shown in Figure 42. The Initial Stage is characterized by sinkholes on the surface and cavern development below the water table. During the Main Stage of development the water table is below the cave system, and sinkholes have increased in size and partially filled with collapse breccia. The caverns have accumulated a layer of cave sediment consisting of debris from collapsing walls and ceilings and speleothems have begun to develop. In the Late Stage, a karstic terrain with significant relief has developed, with collapse and filling of sinkholes and remnant rundkerran of less soluble, tighter limestone.

In a mature karstic regime where sufficient thickness of carbonates exist, all three of these stages can exist contemporaneously, and may develop spatially in both vertical and horizontal directions. The land surface will have developed Late Stage karstic terrain, while just below, speleothems have formed in caves and caverns. Below the water table, new caves are being actively developed. Figure 43 is an attempt to combine all three stages into one diagram to illustrate this process as it might occur.

Stratiform Breccias

Stratiform breccia is a phenomenon significantly different from the more common regional karst described above. Its existence has been noted in the literature (Lynch, 1990, and Choquette and James, 1988), but little

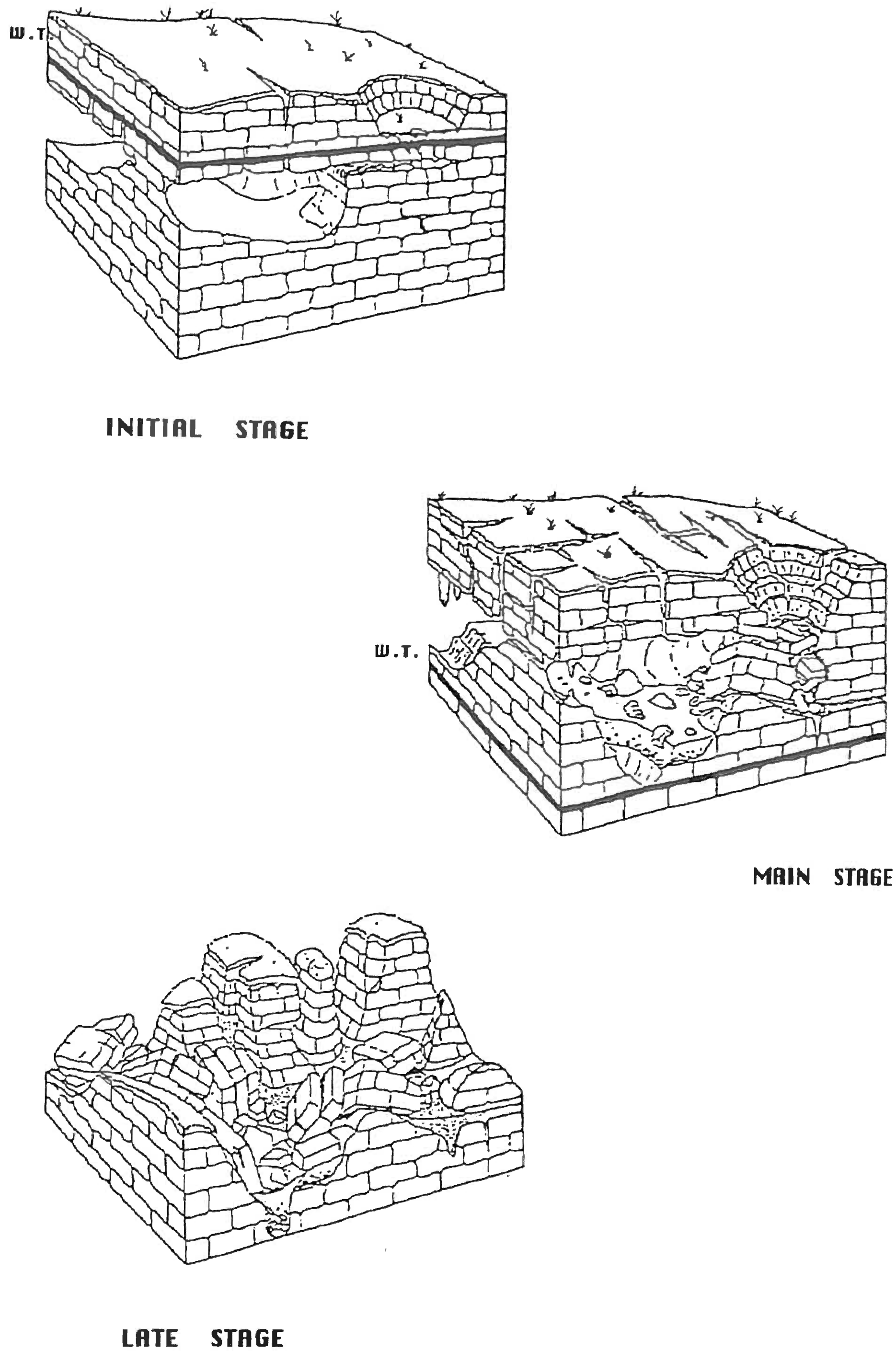


Figure 42. Diagrams of three principal stages of karst development (Lynch, 1990).

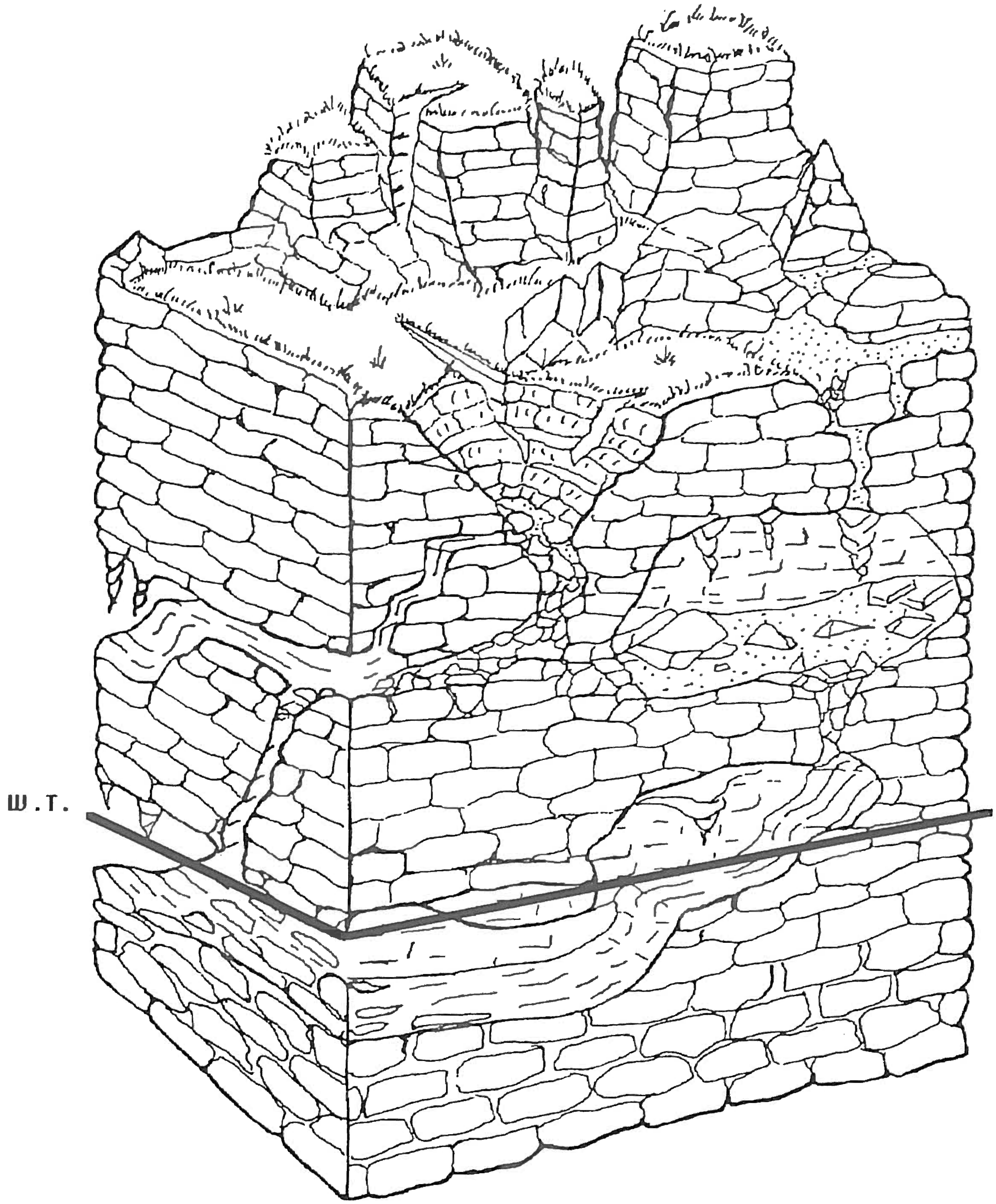


Figure 43. Karstification model combining Lynch's three stages.

has been conjectured as to its mode of generation, nor has a proper definition been offered. The principal karstic phenomenon within the red beds is stratiform breccia; therefore I shall attempt to describe it as fully as possible (see Chapter IV, Karstic Features) and to propose a logical scenario for the generation of this enigmatic feature. The following features are common to stratiform breccia:

1. Crackle and Microdil breccias are absent at many places.

2. Collapse breccia, marked by heterogeneity of clasts and clast-supported, chaotic fabric is the most common type.

3. Less common but certainly not rare is parabreccia, characterized by its mud-dominated fabric.

4. Clasts can be moderately well-rounded, indicating that a certain amount of transport occurred.

5. Most, but not all, show no red color, indicating that either small amounts of ferrous minerals were present, or the sediments had little exposure to oxygen.

6. Bed contacts are sharp or erosional.

7. Adjacent beds are marine carbonates, most commonly upper intertidal facies.

8. Small-scale dissolution features such as solution cavities and sinkholes are common.

Several conclusions can be drawn from these observations. First, because these deposits are bedded and do not cut across bedding planes, they may be a type of cavern floor deposit. Their rubbly nature is conducive to preferential erosion at the surface, which makes their lateral extent difficult to determine. One possibility is that they might be fillings of solution-enlarged bedding planes. Laminar flow along bedding planes in low-permeability carbonates can result in significant dissolution (Choquette and James, 1988), particularly if there is significant dip of bedding to accelerate the process. However, laminations of terra rossa in Sample 11 (Figure 37), parallel to bedding, indicates little or no dip to the beds during karstification.

Second, from their rounded clasts and dearth of cave-roof facies (crackle and microdil breccias), stratiform breccias seem to have undergone slightly more transport than other karstic breccias. Mud dominated cavern-fill parabreccia that in some instances has little chaotic arrangement of clasts has probably undergone an insignificant degree of transport (see Figure 44). One sample, R8, appears to have clasts within clasts, indicating two possible episodes of brecciation (Figure 45).

Third, the scarcity of oxidized ferrous minerals within the breccias and the proximity of marine deposits suggests that a near-shore depositional environment is a good possibility, such as marine phreatic zones or mixing zones. Diagrams in Figure 46 illustrate an environment where such deposition could have occurred.

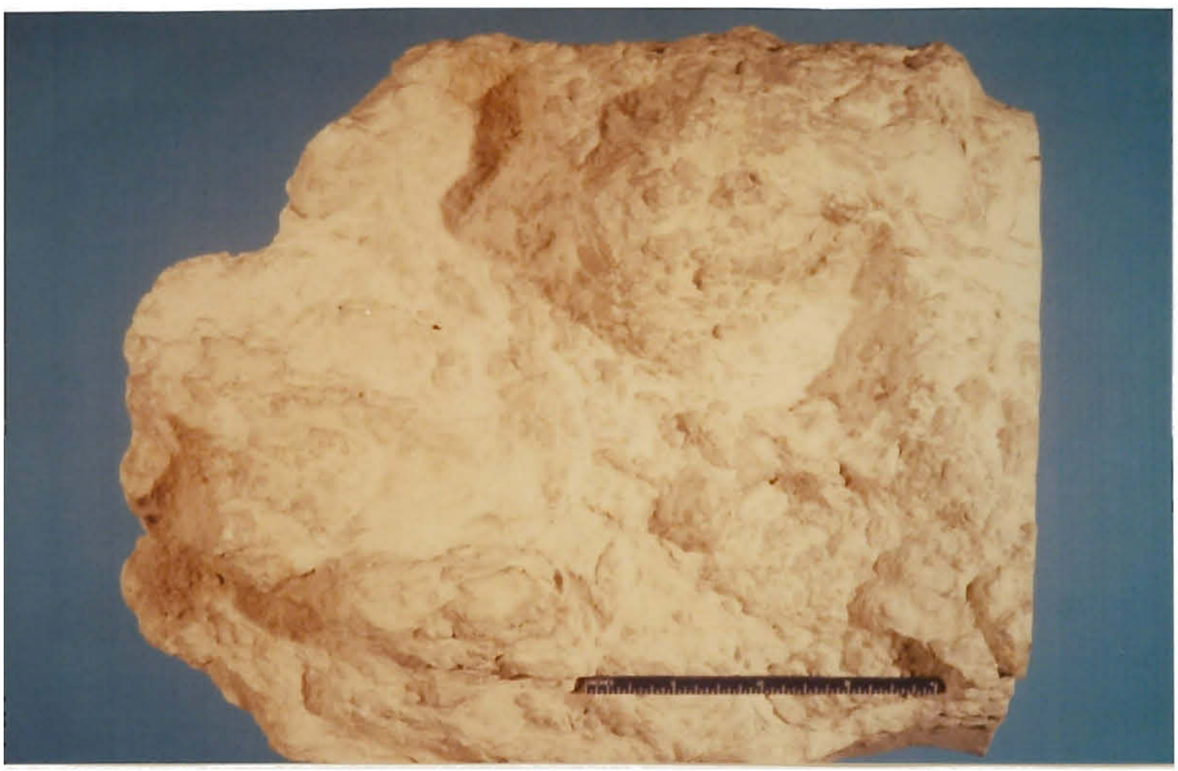
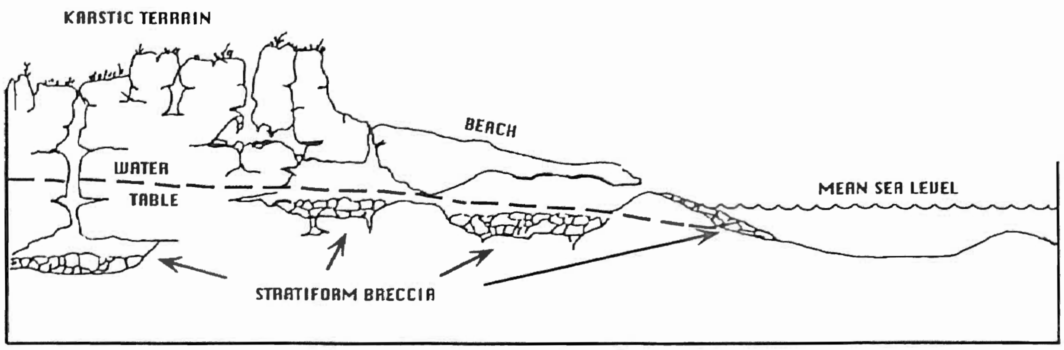


Figure 44. Photograph of mud-dominated, cavern-fill parabreccia.

Figure 45. Photograph of hand-sample of collapse breccia which may have two episodes of brecciation. Fractures at arrows show almost no dislocation of clasts, but are secondary to primary chaotic collapse breccias.



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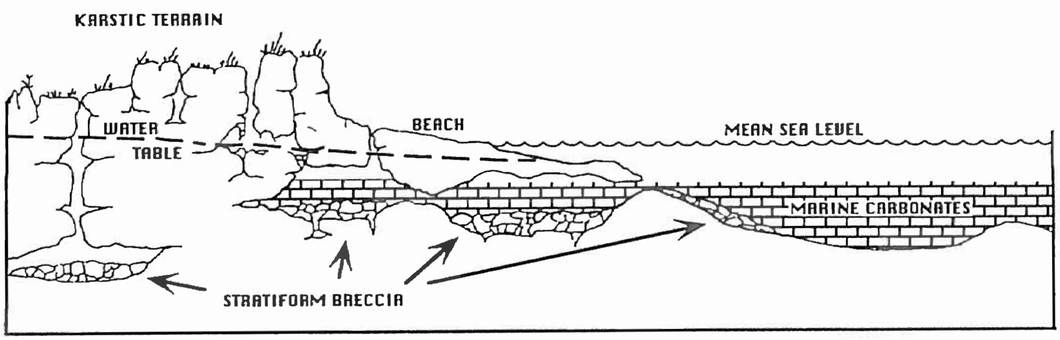

B

Figure 46. Near-shore karstification models. Diagram A illustrates active karstification during a lowstand. Diagram B shows transgression and marine deposition.

CHAPTER VI

CONCLUSIONS

The Ordovician Period was a time of significant accumulation of carbonate rocks in southern Oklahoma. These rocks were deposited in classic ramp environments of shallow epeiric seas that covered large areas of the North American Craton. The Lower Ordovician West Spring Creek Formation of the Arbuckle Group was deposited during sea-level fluctuations that resulted in repetitive shallowing-upward cycles or parasequences.

Depositional environments of the West Spring Creek ranged from upper subtidal, characterized by well-preserved fossils and oolite shoals, through intertidal high-energy zones, upper intertidal restricted zones and lagoonal regions. The shallower intertidal zones were terrain of fossil fragments, stromatolites, and small amounts of terrestrial deposits. Lagoonal and tidal-flats facies are muddier, commonly laminated, bioturbated, and conspicuously lacking in fossils.

The complex diagenetic history of this formation is clouded, due to the relatively high solubility of carbonate rocks. This allows dissolution and precipitation to destroy traces of earlier events. The paragenetic sequence, therefore is limited to only that which could be ascertained from the relatively few thin sections that were examined. Early diagenetic events consisted of precipitation of marine phreatic calcite, dolomicrospar, and pyrite. Microspar calcite, chalcedony, chert, and xenotopic dolomite formed during early burial. Fine-grained idiotopic dolomite and meteoric sparry calcite precipitated as burial progressed. As the rocks subsided further into the basin, thermal dolomite formed. Hematite was concentrated along stylolite seams. Uplift of the formation resulted in exposure to fresher formation waters, and chamosite and other clays along with drusy calcite occluded much of the porosity. Hematite formed as an alteration product of ferrous minerals such as pyrite and ankerite, and calcite began to replace much of the dolomite.

Another feature of the diagenetic process is dissolution, and this often progresses to the extent that karst forms. The West Spring Creek has undergone various episodes of this process, beginning even before deposition was complete. In the study area the stratiform breccia zones within the upper red-bed sequence are the most significant evidence of syndepositional karstification.

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APPENDICES

APPENDIX A

LITHOLOGIC LOG

APPENDIX A KEY

1. The bed numbering system in the first column corresponds to Fay's 1969 measured section.

2. Sample numbers:
   A. WSC - West Spring Creek
   B. R<u>xx</u>.<u>x</u> - Indicates red bed sequence

3. Bed Numbers (following the number)
   C. o - oolite bed
   D. r - red bed
   E. s - sandstone
   B. b - breccia

APPENDIX A

Lithologic Log of the
Upper Red Bed Sequence

Bed	Sample	Description
37s	WSC5 R48	Eight feet of white to yellowish tan, fine grained, well-sorted, well rounded, calcite-cemented quartz arenite, characterized by trough cross bedding and symmetrical ripple marks. The weathered surface often is stained a dark grey to black and has limonite and pyrite specks. It is capped by one foot of grey limestone with layers of chert nodules.
38	R44	One foot of tan, rubbly and burrowed dolomitic wackestone with grey chert.
39r		Two feet of poorly indurated red-brown marl, fine to medium grained, nodular, with some red brown shale.
40.		Five feet of lavender, laminated, burrowed, micrite with six inches of green shale at the top. Alternating red and greenish-grey laminae give this rock its lavender color.
41r	R43	One and one-half feet of red-brown marl with greenish-grey to red-brown shale in the upper part.
42b	R42 R42.1 R41 R40	Two feet of yellow-brown to greenish-grey dolomitic limestone and marl, massive at the top, thin bedded below, with grey to tan chert at the base. This is a brecciated zone. R42is a dolomite, while R42.1 is a sample of red and grey thin-bedded to laminated wackestone. This bed also contains a brecciated zone from which Sample R41 was removed. R40 is a sample of the basal dolomitic shale.

43.		Five and one-half feet of moderately well-indurated, laminated limestone with six-to eight-inch beds. The coloration shows little variation from the pinkish grey-tan on fresh surfaces, but often weathers with a limonite crust.
44r	R39 R38 R37	Two-foot bed with thinly laminated, weakly indurated shale at the base. The middle zone is a yellowish dolomitic lenticular limestone. There is pinkish thin laminae of limestone near the top, moderately well-indurated.
45o	WSC7a WSC7b	Three feet of grey oolitic limestone with small LLH stromatolites in top one-half inch. It is underlain by a grey, interclastic wackestone to packstone.
46r	R36	Three feet of reddish-brown, fine-grained, moderately well-indurated limestone with some interbedded red and yellow shale and marl. R36 is a red shale sample.
47b	R35 R34	One foot of grey mudstone, sample R35 of which is a parabreccia from the top. Sample R34 is a basal wackestone with alternating laminae of fine flat-pebble interclasts, ooids, and bioclastic debris.
48r	R33	One and seven-tenths feet of shaley red marl, with thin laminae at the top and becoming less competent near the base.
49o	R32 R32.1 R31	One and one-half feet of the most typical habit of oolitic limestone in this section. It is very well indurated, grey, fine to coarse-grained and has associated peloids and interclasts at various horizons. This could possibly indicate tidal channels and/or "back shoal" facies. R32 is a dolomite. R32.1 is a microspar with approximately 30 per cent very fine, well-sorted and rounded quartz sand. R31 is a sample of ooids and grapestones in a micrite matrix which has largely been replaced by sparry calcite.

50r	R30 R29 R28 R27 R26	Six and eight-tenths feet of marl, limestones and shales, whose colors range the gamut from grey through shades of red to grey-green and yellow. R29, R27, and R26 show strong hematitic banding and repetitive grain size alternation indicating possible seasonal variations in deposition.
51	R25 R24	Six feet of grey limestone which is thinly bedded to thinly laminated, frequently bioturbated, hematitic, with coarsely crystalline diagenetic calcite in a micritic matrix.
52o	R23 R23.1	Nine-tenths feet of grey, oolitic, pelletal limestone. Most clasts have pronounced micrite envelopes and are not very well sorted, indicating tidal channel or "back shoal" deposition.
53r	R22 R21	One and two-tenths feet of reddish-brown, poorly indurated marl and shale, yellowish at the base. R22 is a sample of the red shale, and R21 is a sample of the yellowish-grey limestone at the base. In hand sample and on outcrop this appears shaley or even slightly sandy, but is wackestone with diagenetic sparry calcite and chert.
54	R20 R19 R18 WSC8	Three and one-half feet of grey, laminated, moderately well-indurated, often pelletal limestone, with limonitic weathered surfaces at the top and at the base. R20 has three zones, all of which have small stringers of very fine sand grains. The middle zone of wavy lamination has fennestral porosity occluded with sparry calcite. R19 is a bioturbated peloidal mudstone, with a narrow zone of flat pebble storm deposits. Detrital very fine-grained sand is a major constituent of R18, which is a peloidal grainstone.

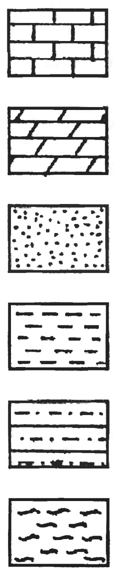
55rb	R17 R16 R15 R14 R13 R12 R11 R10	Twelve and one-half feet of reddish-brown limestone, fine-grained, laminated to shaley. There is a lenticular grey collapse breccia in the middle which has one six-inch solution cavity rimmed with calcite crystals and another to the right of the first which is filled with karstic breccia. R17 is a hematitic mudstone and R16 has detrital quartz in solution pipes and shows considerable soft sediment deformation beneath a one-half inch zone of LLH stromatolites. R15 is a beautiful example of a small sink hole and R14 is a mini breccia. R13 is hematitic wackestone, and R11 and R12 are red shales. R10 is terra rosa with bedding planes parallel to adjacent beds.
56b	R9 R8 R7	Four and one-half feet of tan to greenish-grey fine-grained mudstone, well-indurated with a basal two-foot bed of collapse breccia and mud dominated parabreccia.
57r	R6	Five feet of tan to pinkish-lavender thinly bedded to laminated wackestone, often nodular, with a thin bed of shale at the base, form the base of the upper red bed sequence. R6 was taken from the top of the bed, and is hematite and calcite cemented. R1 through R5 are similar samples of hematitic marl, often nodular, with some soft sediment deformation and solution channel infill of lime mud and detrital quartz.

APPENDIX B

CORE PETROLOG

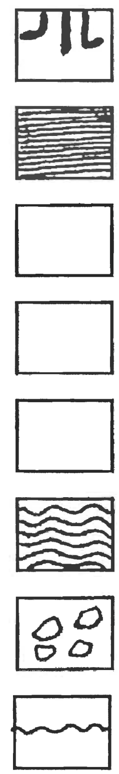
PETROLOG KEY

LITHOLOGY



- LIMESTONE
- DOLOMITE
- SANDSTONE
- SHALE
- SILTY SHALE
- MARL OR CALCAREOUS SHALE

SEDIMENTARY STRUCTURES



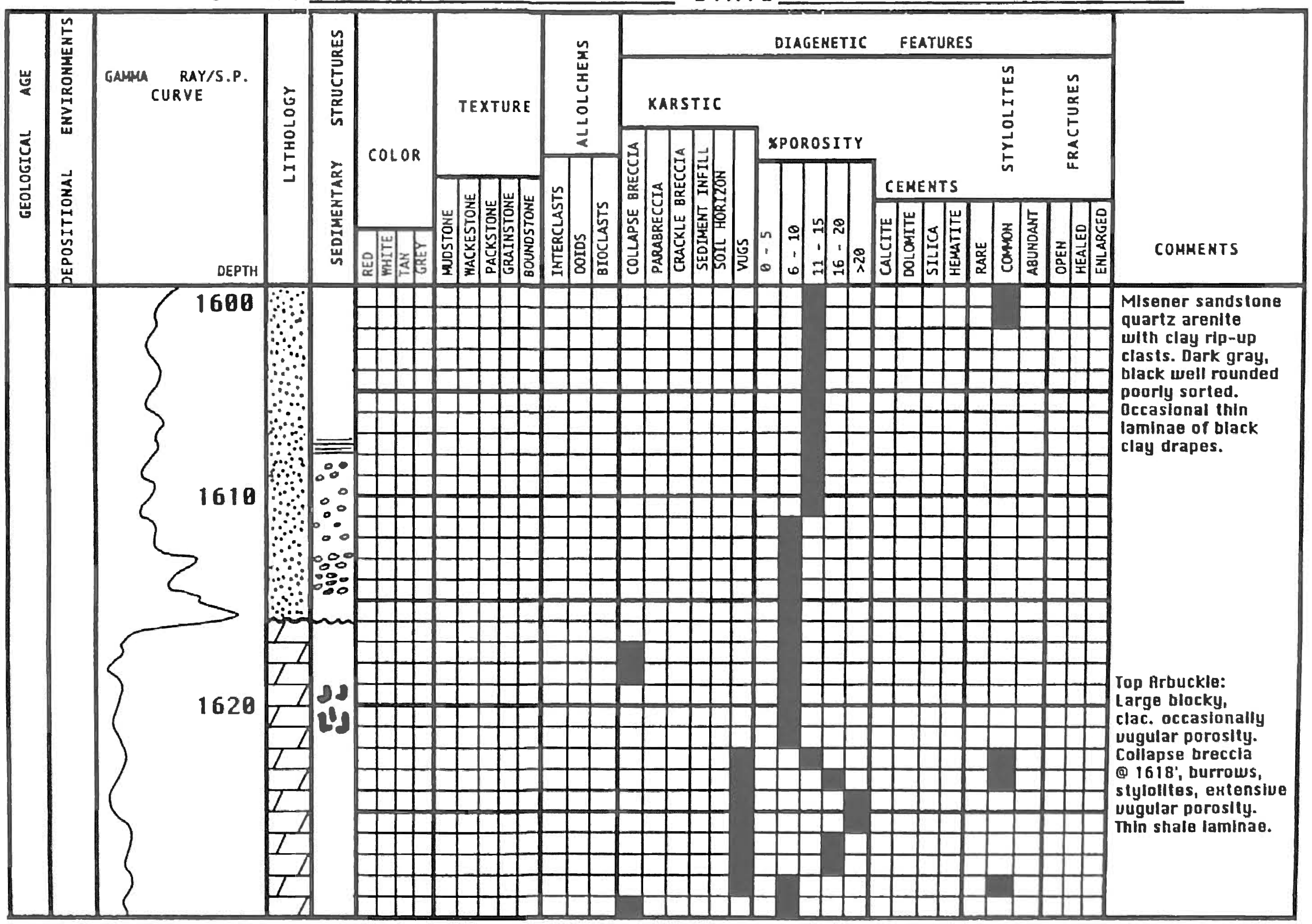
- BURROWS
- THINLAMINAE
- INTERCLASTS OR MUD RIP-UPS
- FOSSILS
- SLUMP STRUCTURES
- DISTURBED BEDDING
- BRECCIA CLASTS
- UNCONFORMITY SURFACE

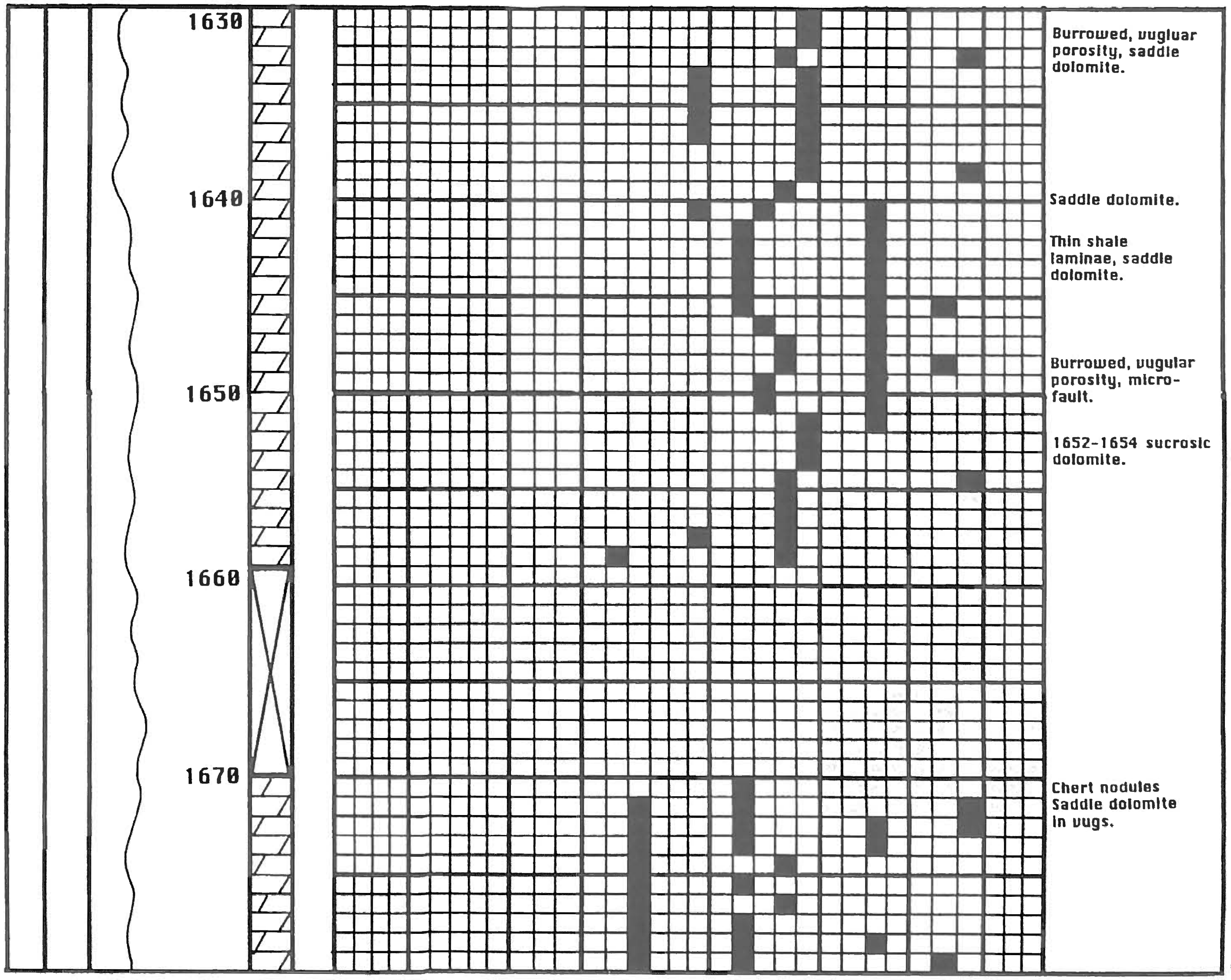
CARBONATE PETROLOG

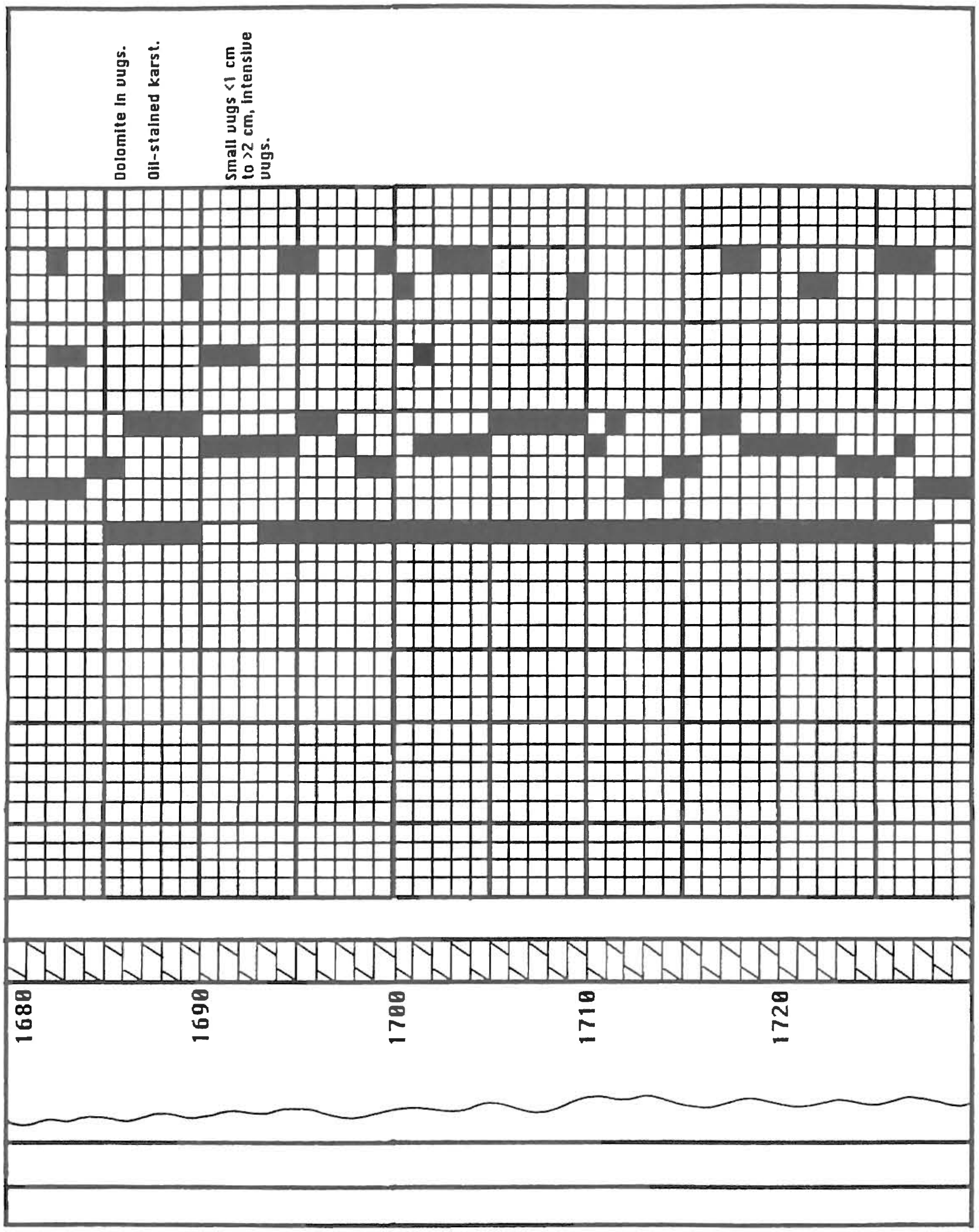
WELL SHAD -4

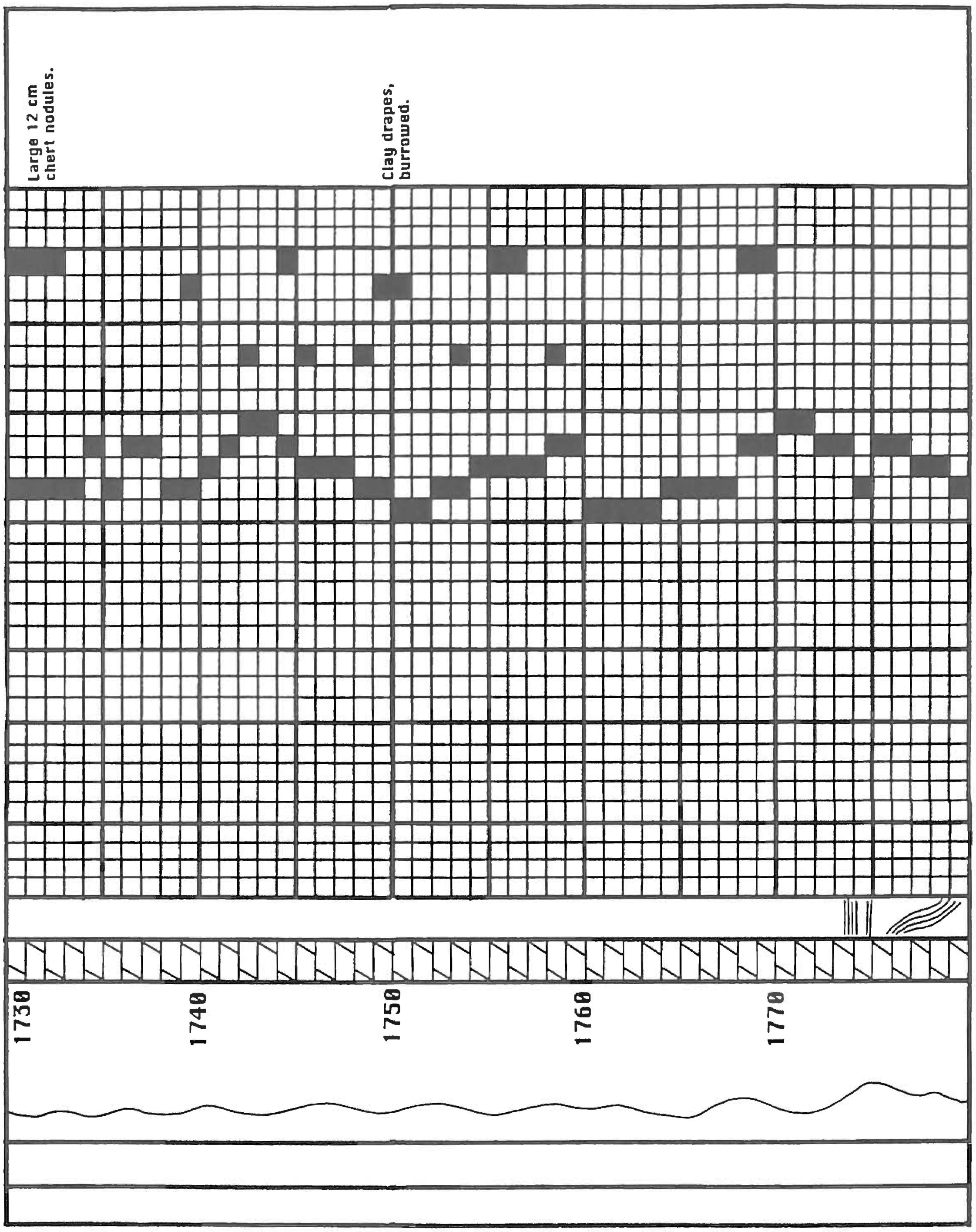
LOCATION SE SE SE SEC. 25 TWP. 21N RNG. 14E

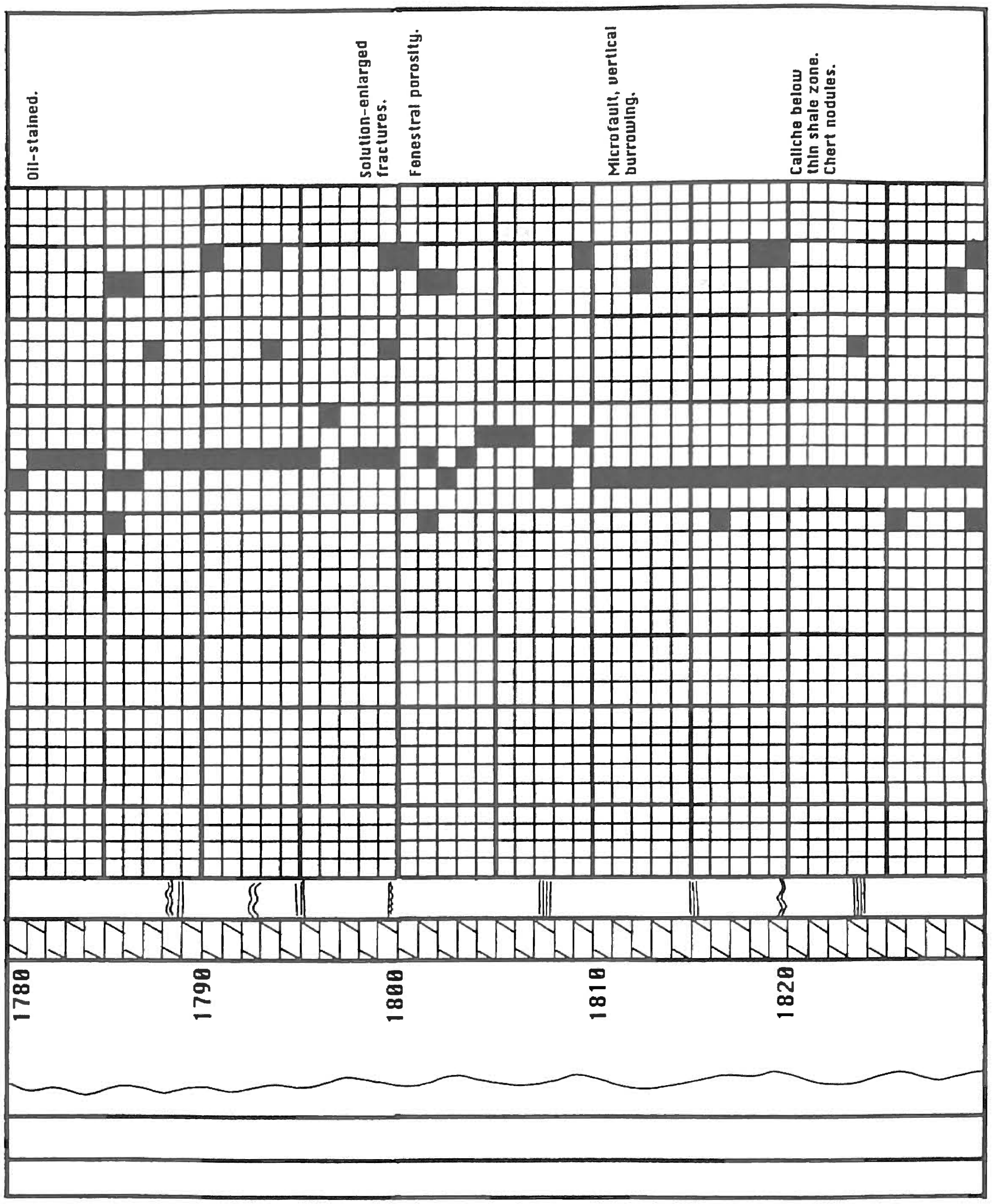
COUNTY ROGERS STATE OKLAHOMA

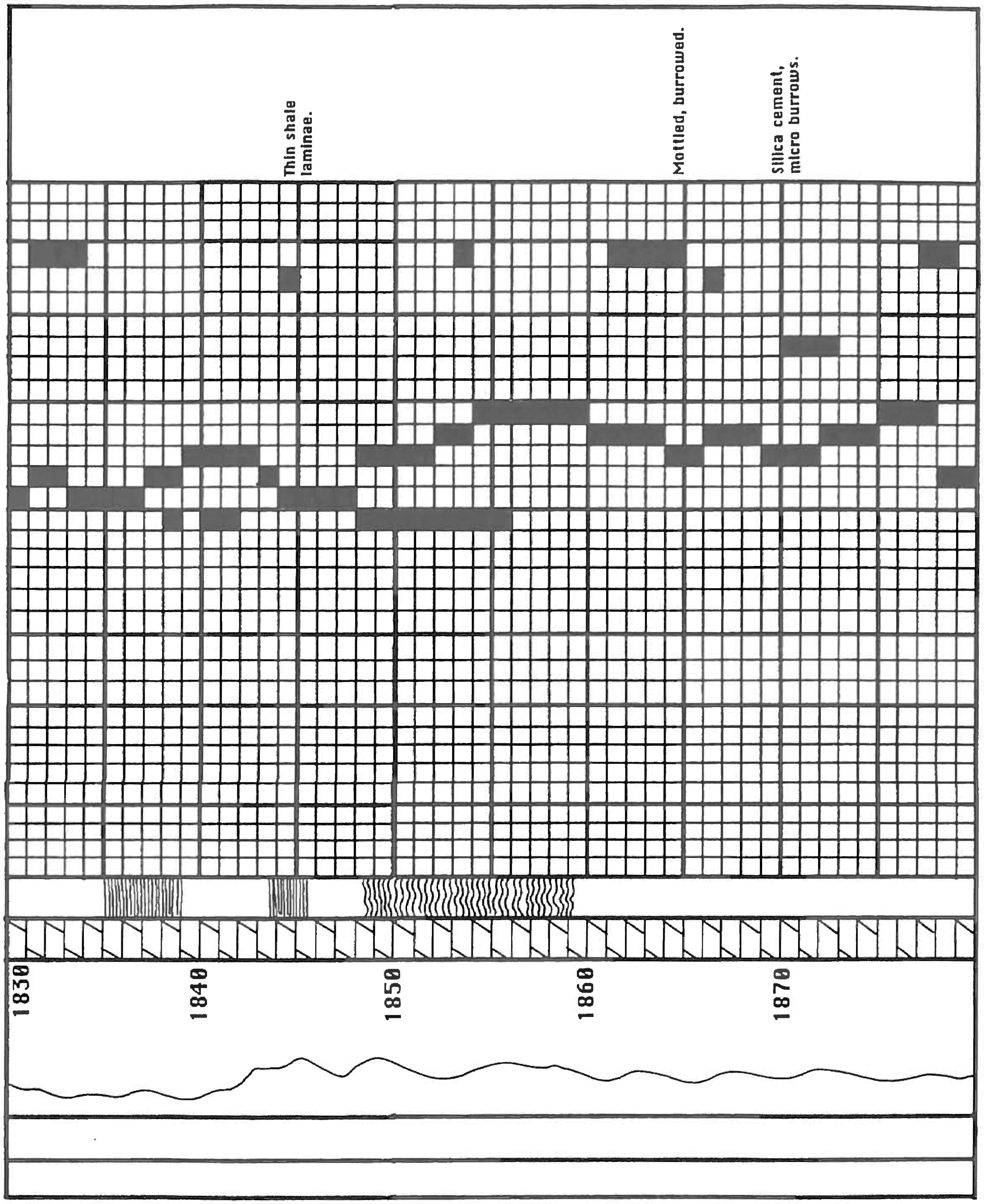


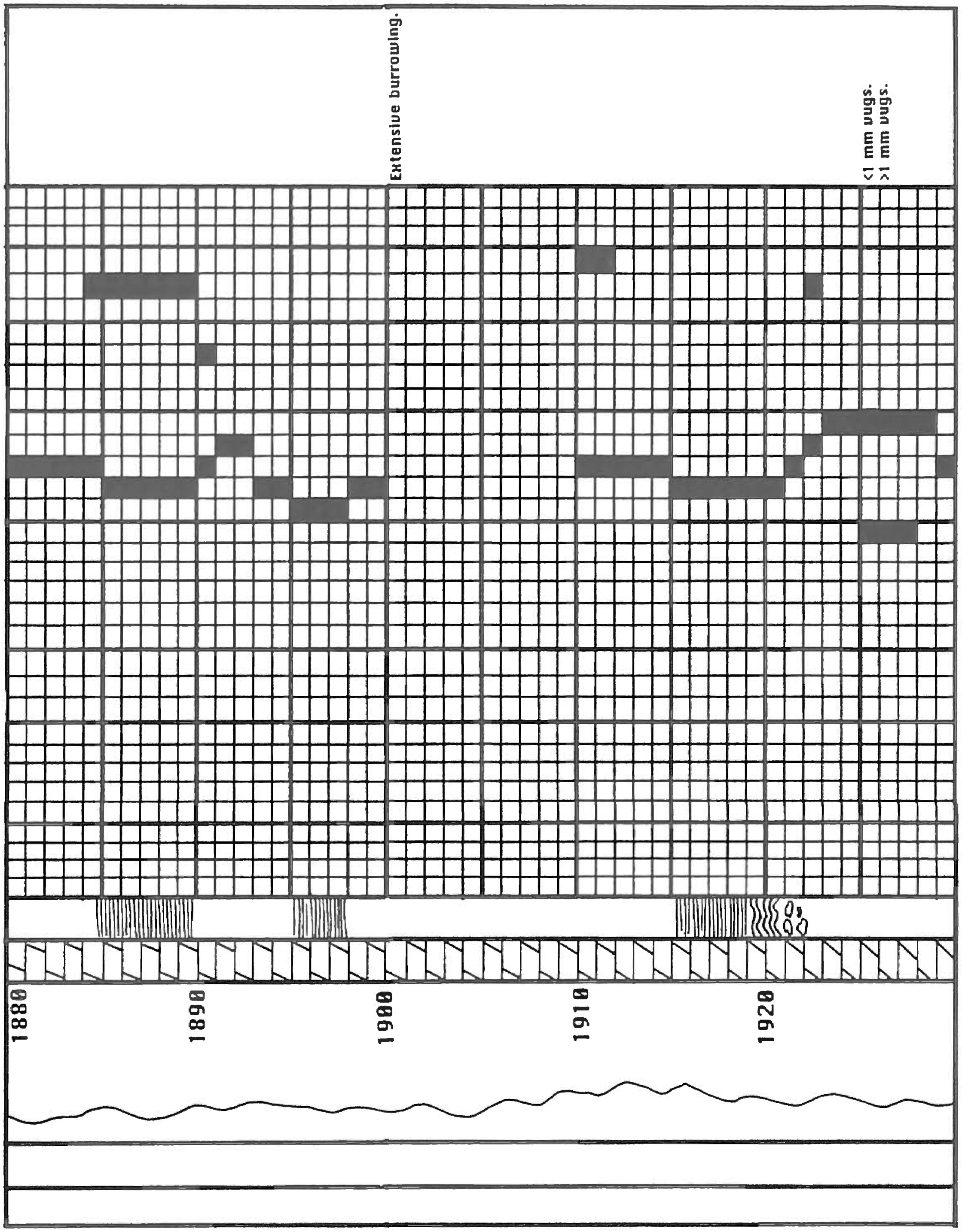

1630
1640
1650
1660
1670
Burrowed, vugluar porosity, saddle dolomite.
Saddle dolomite.
Thin shale laminae, saddle dolomite.
Burrowed, vugular porosity, micro-fault.
1652-1654 sucrosic dolomite.
Chert nodules Saddle dolomite In vugs.


Dolomite in vugs.
Oil-stained karst.
Small vugs <1 cm to >2 cm, intensive vugs.
1680
1690
1700
1710
1720

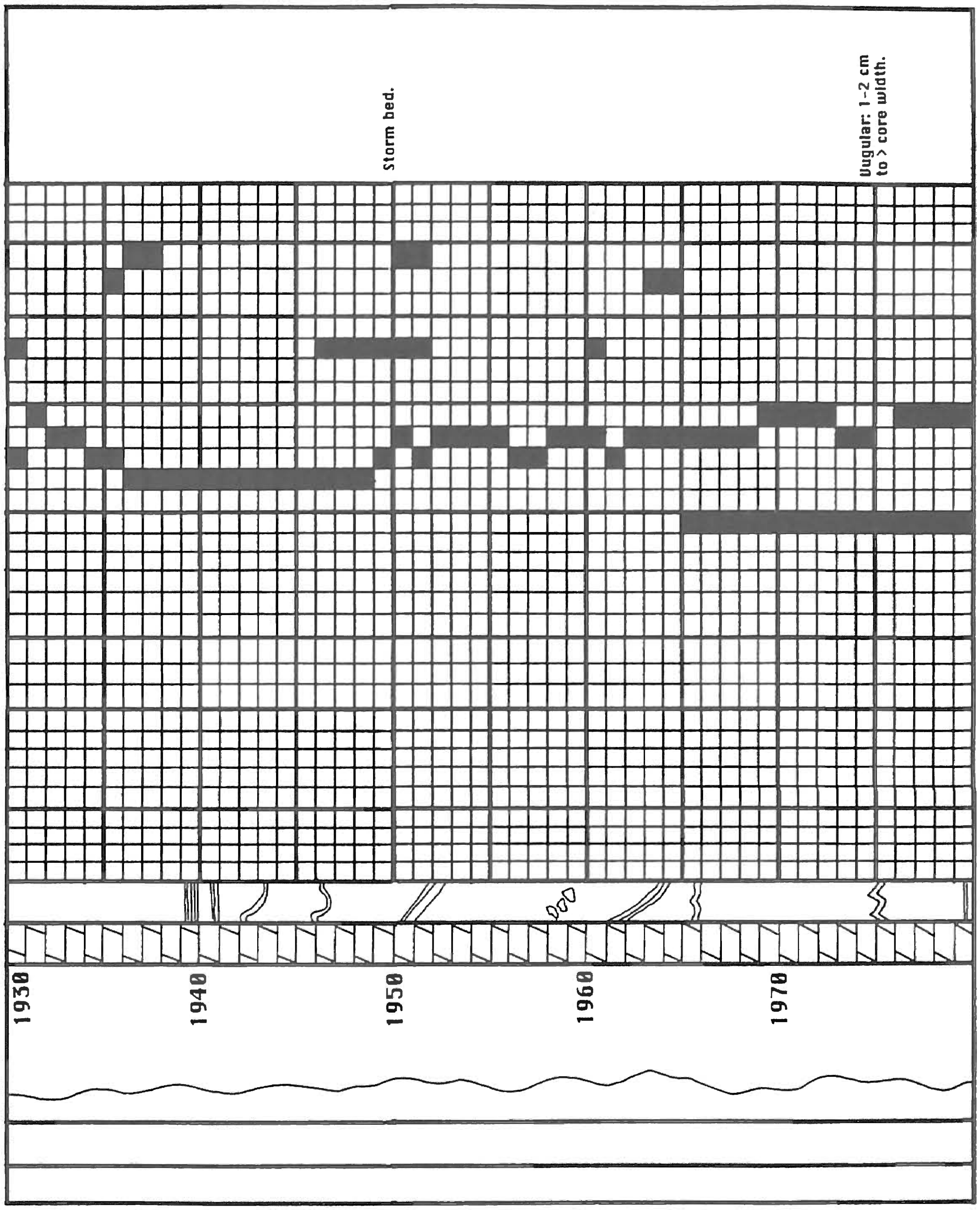

Large 12 cm chert nodules.
Clay drapes, burrowed.
1730
1740
1750
1760
1770

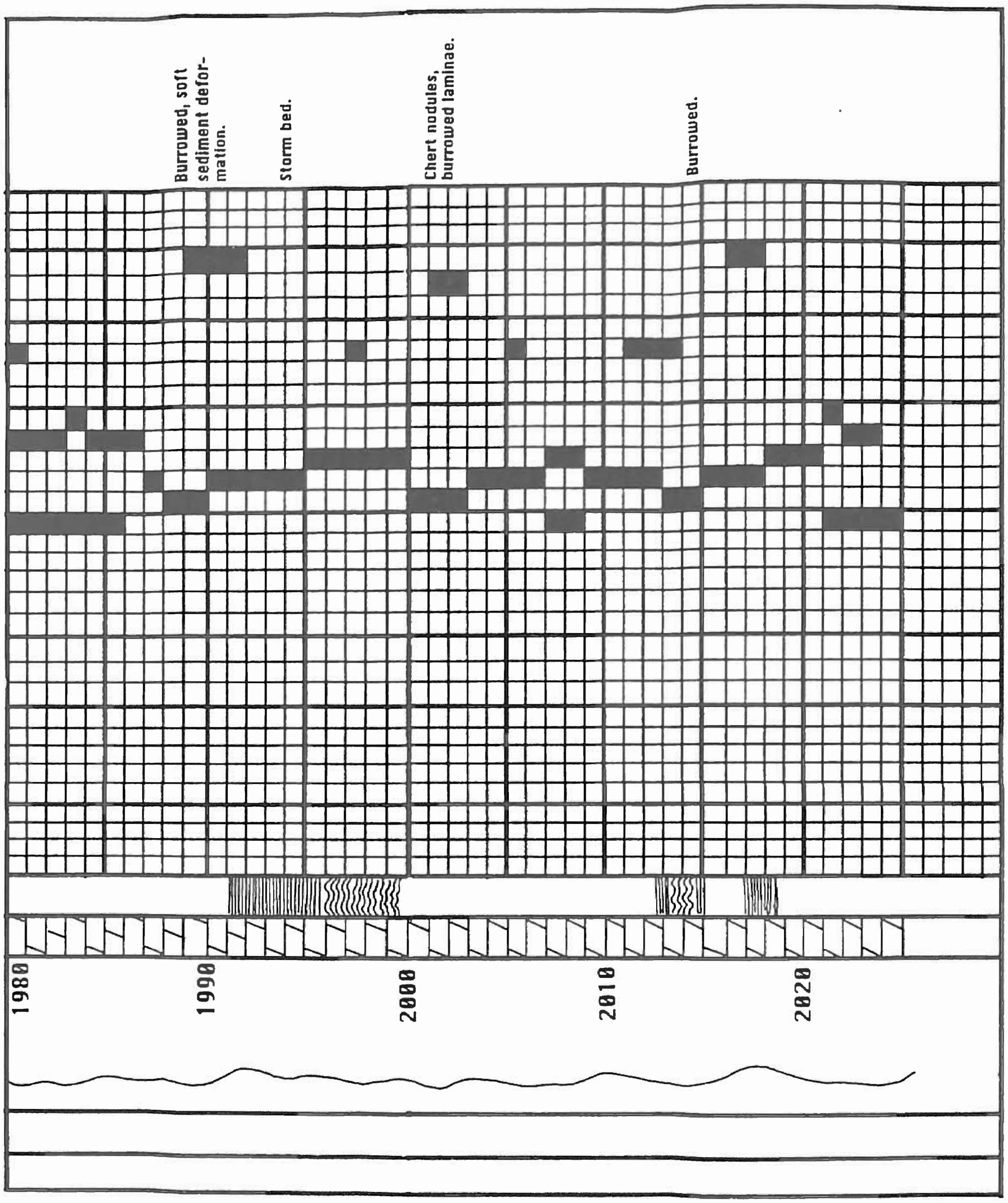

Oil-stained.
Solution-enlarged fractures.
Fenestral porosity.
Microfault, vertical burrowing.
Caliche below thin shale zone.
Chert nodules.
1780
1790
1800
1810
1820


Thin shale
laminae.
Mottled, burrowed.
Silica cement,
micro burrows.
1830
1840
1850
1860
1870



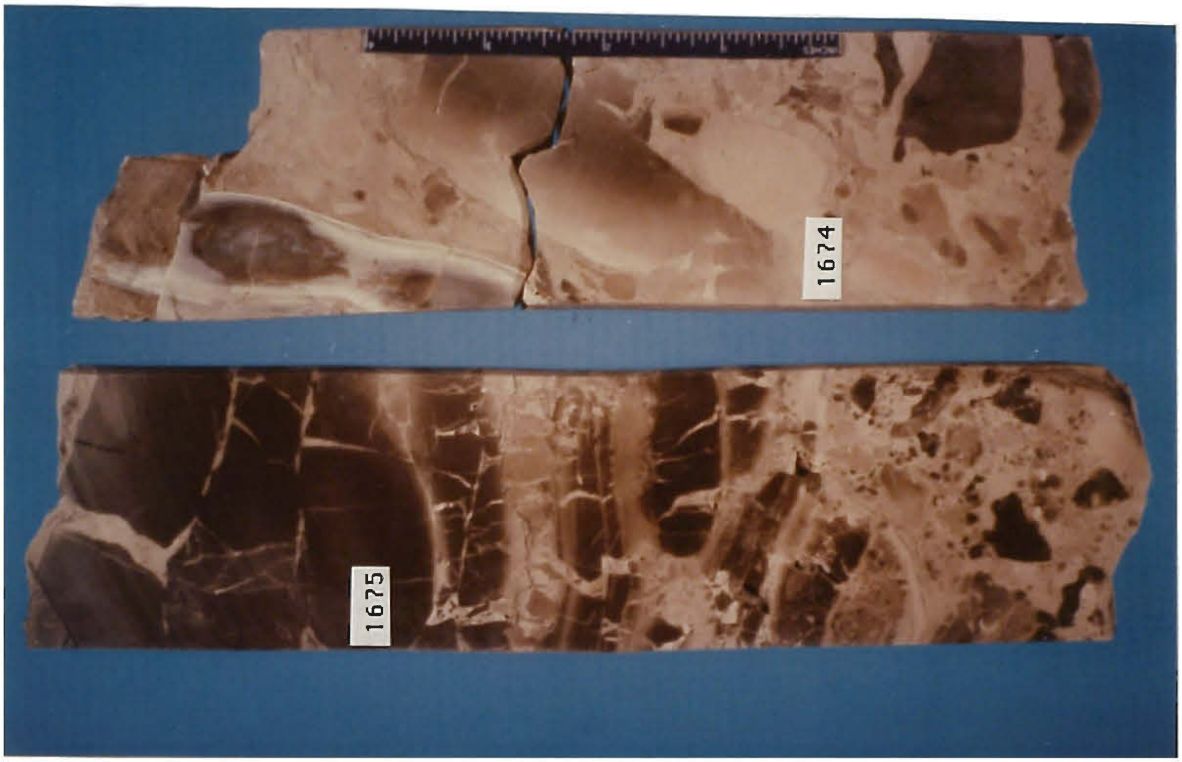
Extensive burrowing.
<1 mm vugs.
>1 mm vugs.
1880
1890
1900
1910
1920

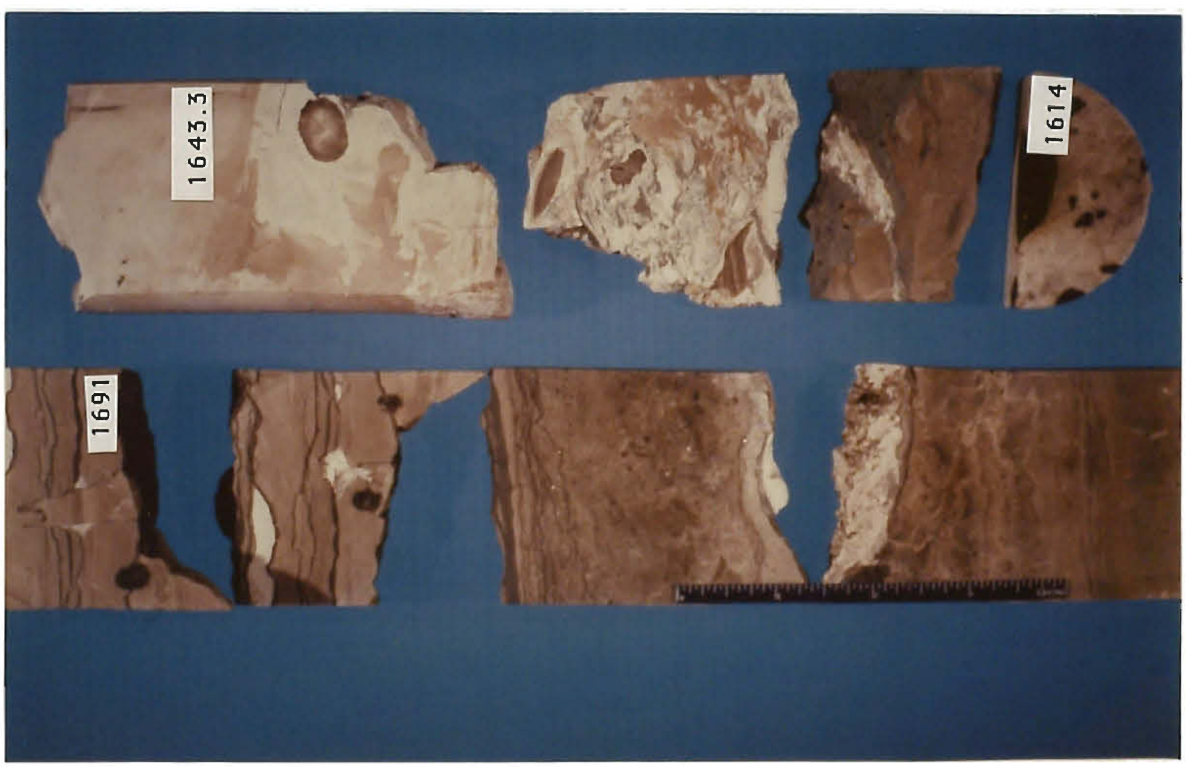

Storm bed.
Vugular: 1-2 cm
to > core width.
1930
1940
1950
1960
1970

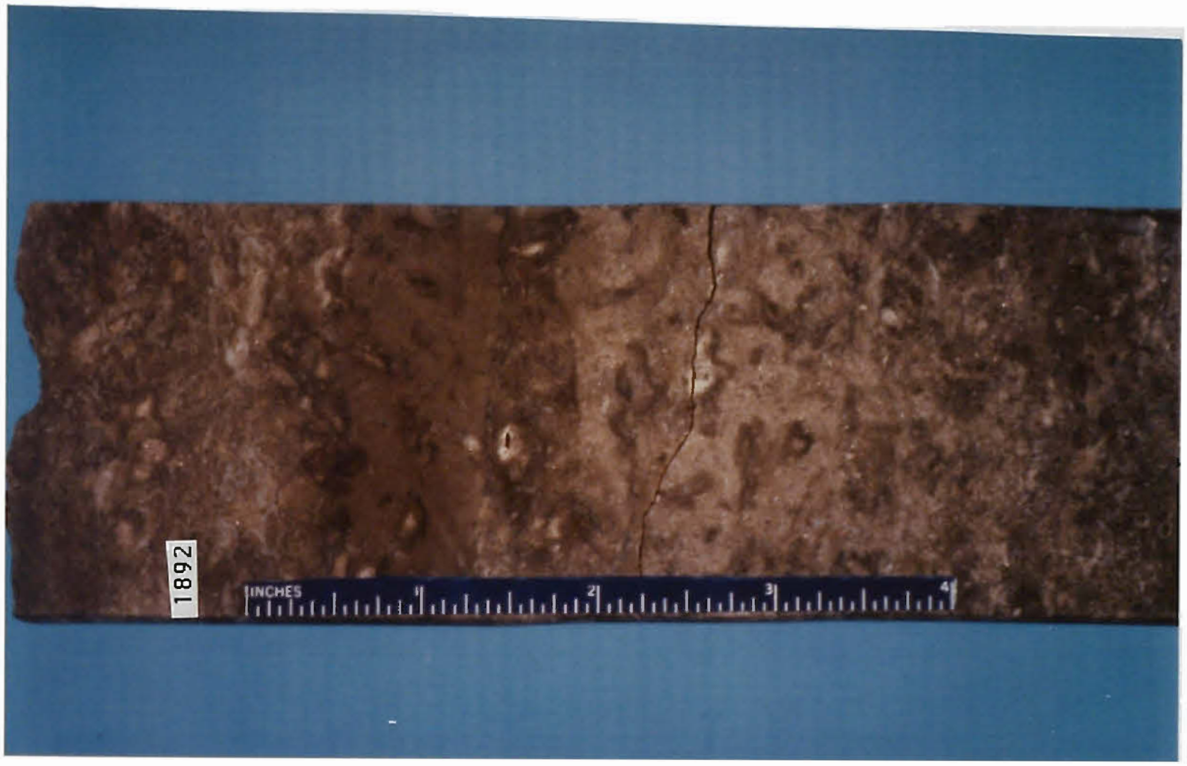

Burrowed, soft
sediment defor-
mation.
Storm bed.
Chert nodules,
burrowed laminae.
Burrowed.
1980
1990
2000
2010
2020

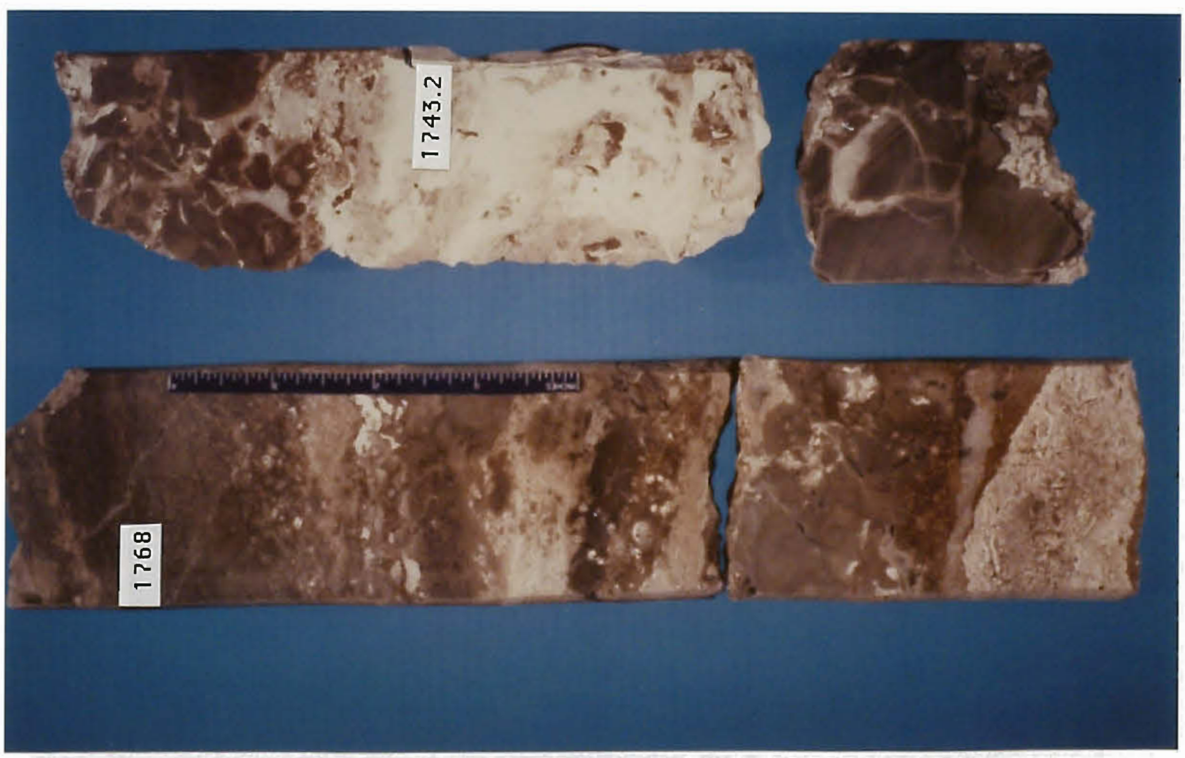
APPENDIX C

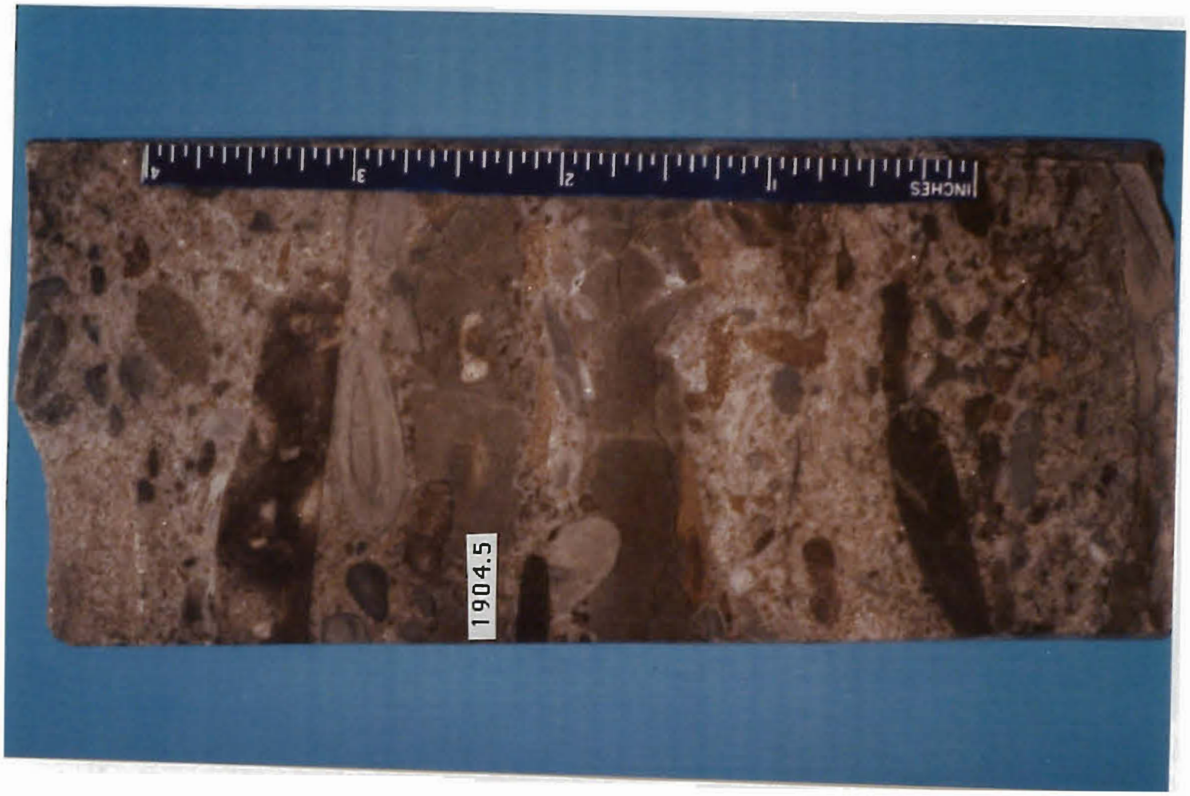
SELECTED CORE PHOTOGRAPHS

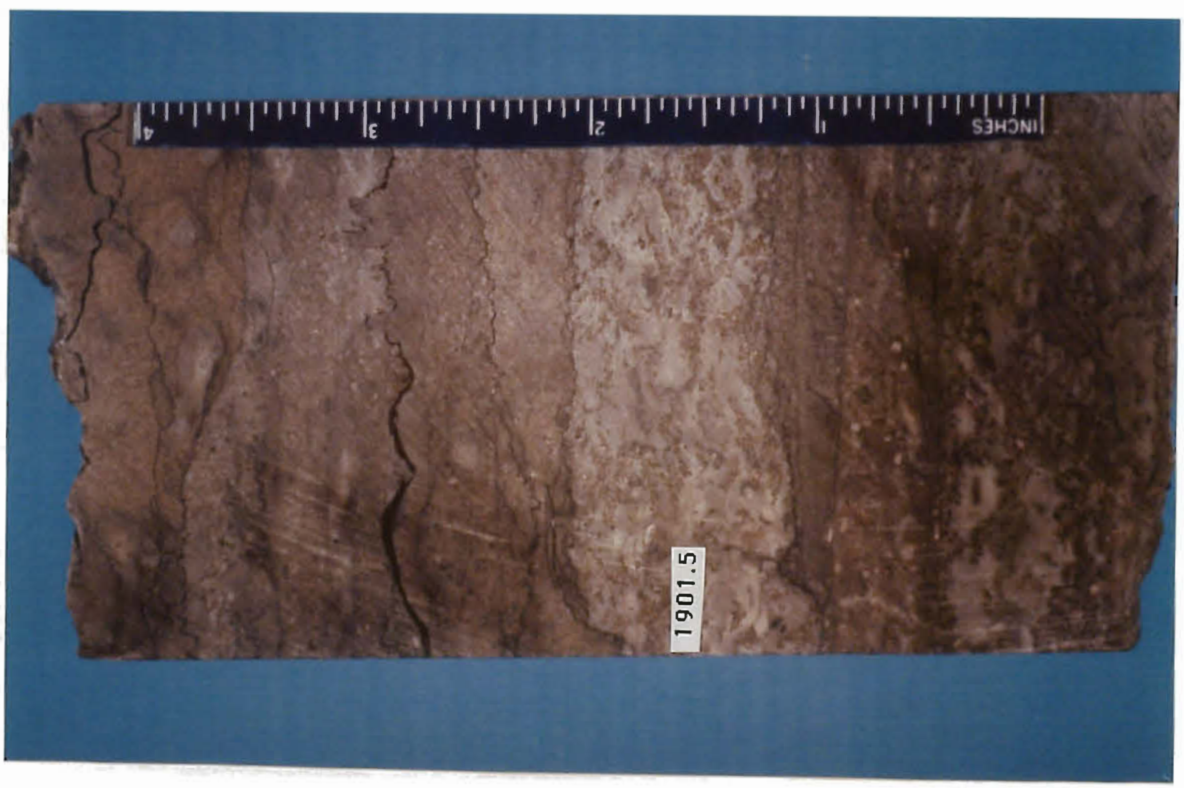

1674
1675

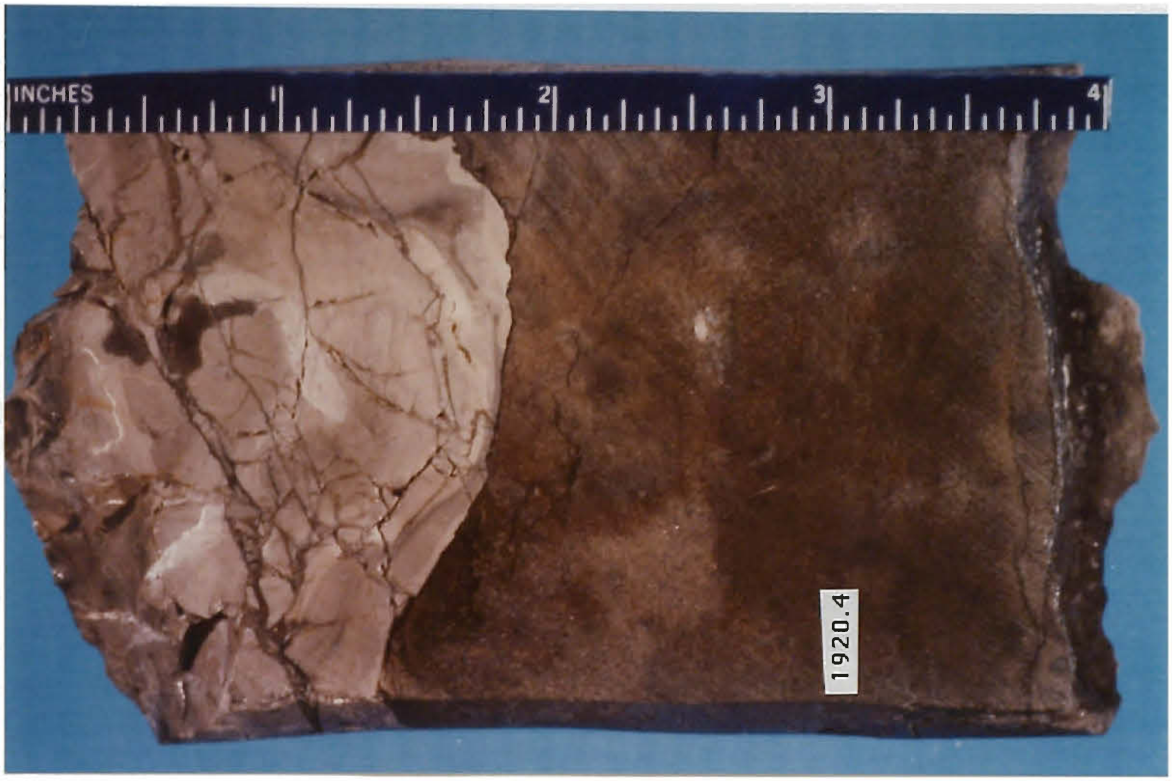

1643.3
1614
1691


1892
INCHES

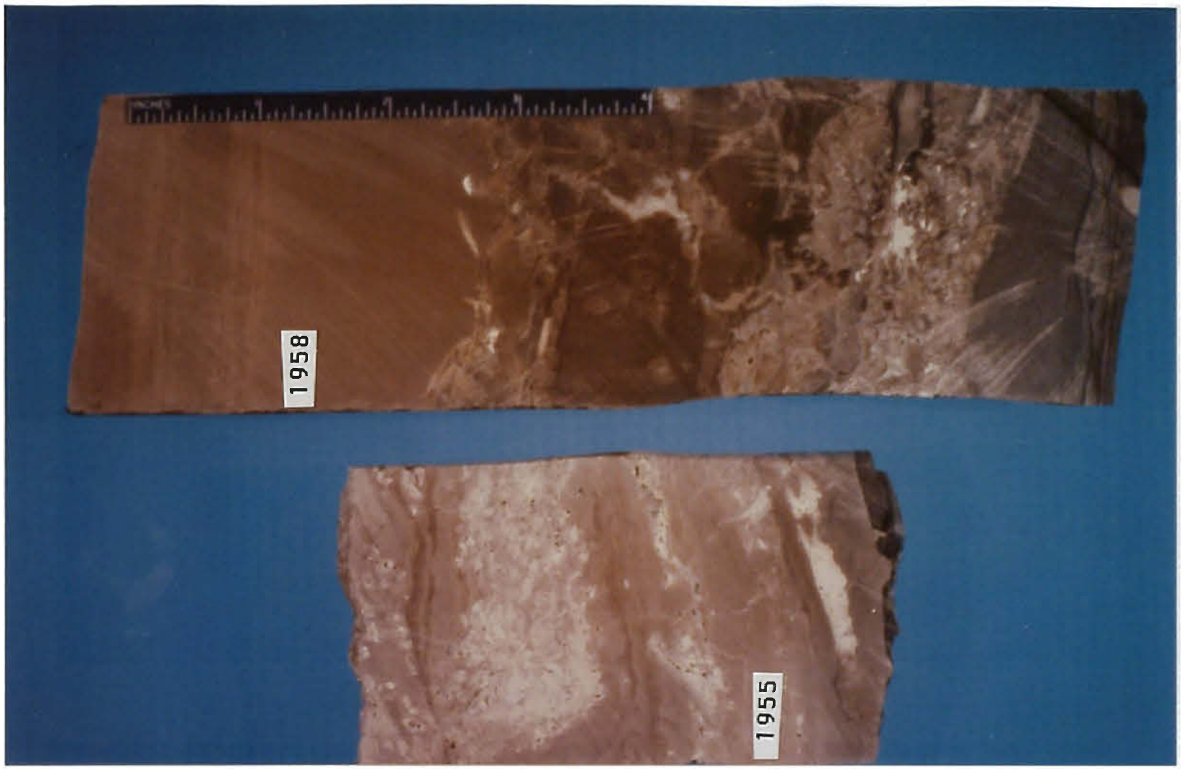

1743.2
1768


INCHES
1904.5


INCHES
1901.5

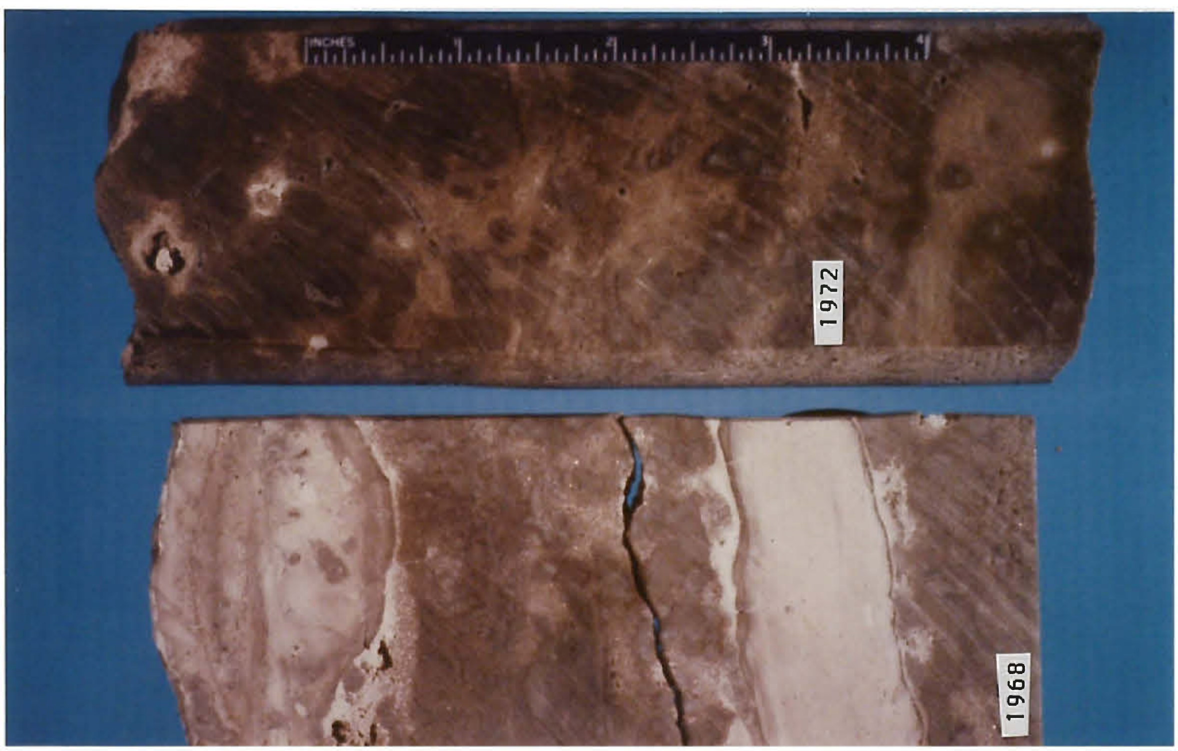

INCHES
1
2
3
4
1920.4

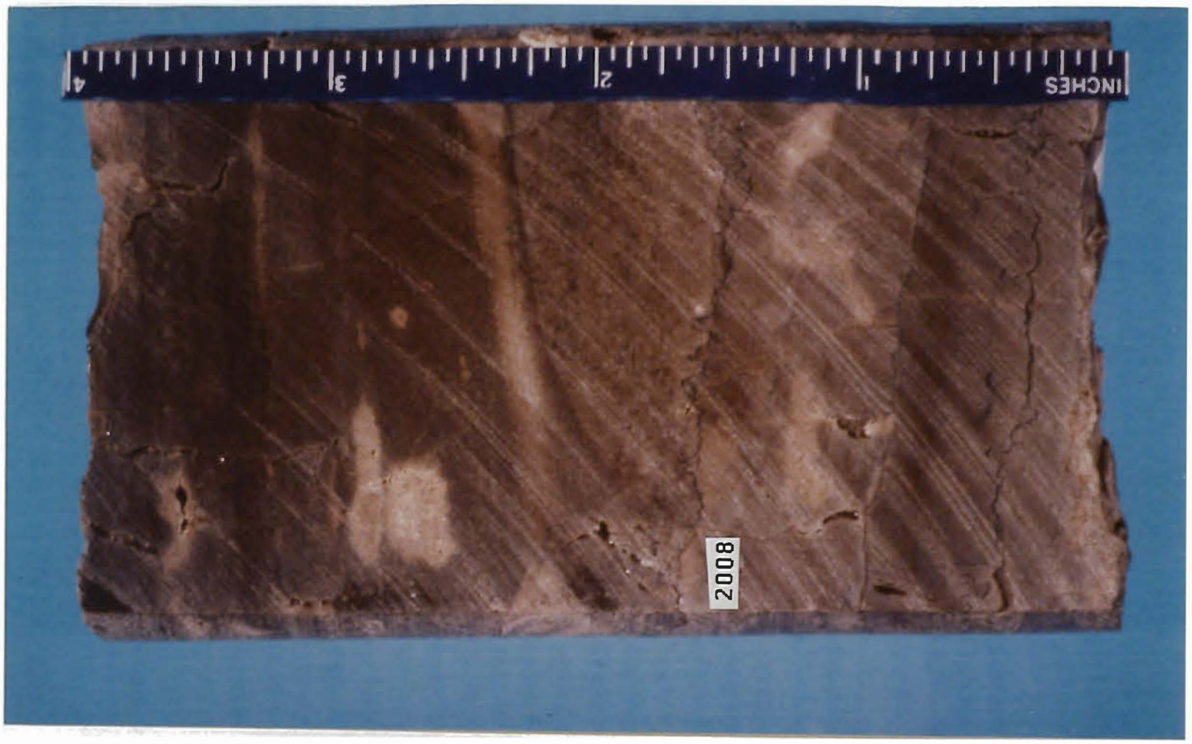

1914
1
2
3
4

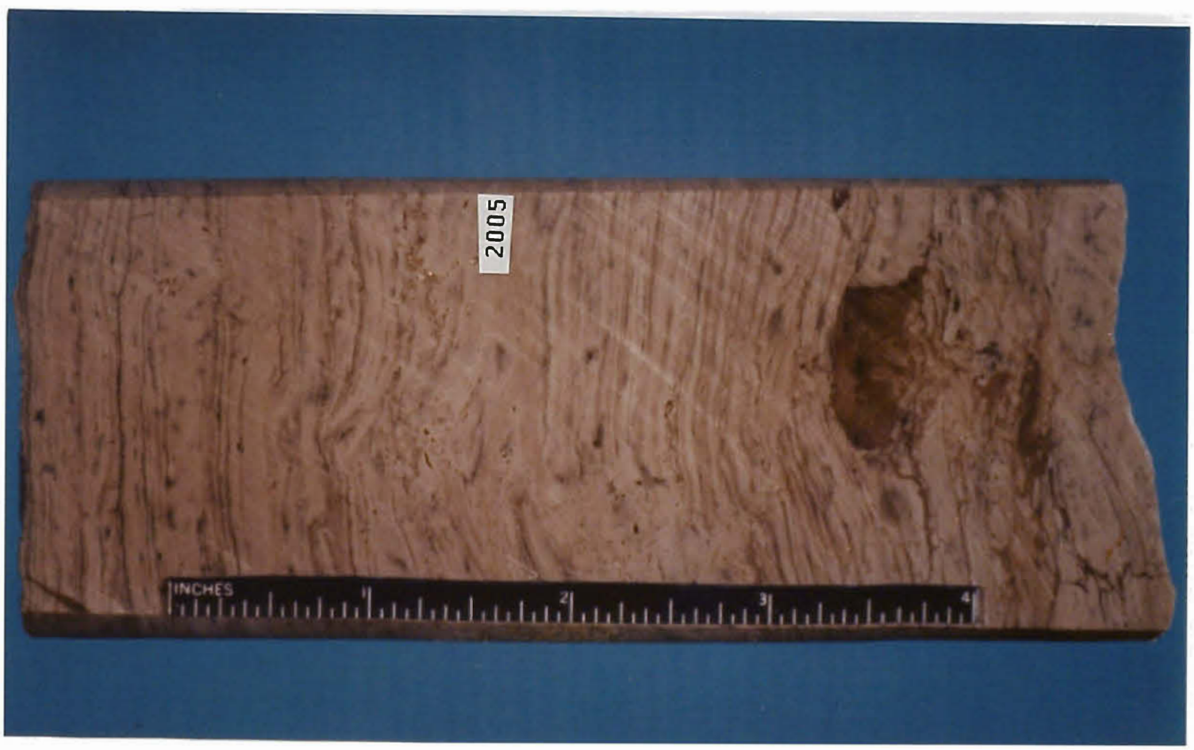

1958
1955


1927.2
INCHES


INCHES
1992


INCHES
1972
1968


INCHES
1
2
3
4
2008


2005
INCHES
1
2
3
4


INCHES
1
2
3
4
2021

APPENDIX D

REPRESENTATIVE X-RAY DIFFRACTOMETRY

CALCULATION OF MINERAL WEIGHT PERCENTS IN BULK ROCK SAMPLES FROM WEIGHT FRACTIONS AND I/I CORUNDUM VALUES

Geologist: Judy Musselman
Sample No: R1 to R 48
West Spring Creek data

Sample Type: Carbonate
Project: Thesis - X-Ray Results

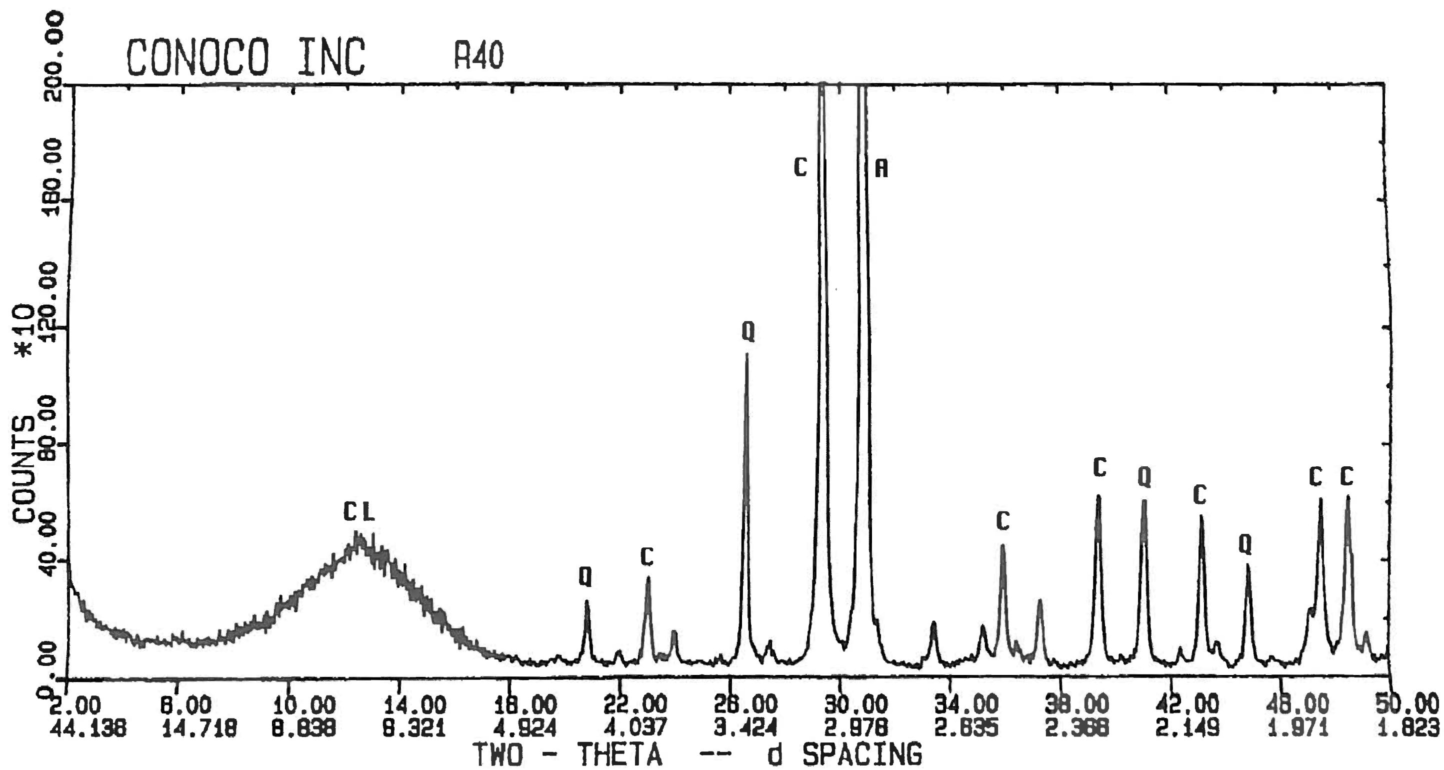
Sample Number	Quartz	Potassium Feldspar	Total Clay	Calcite	Dolomite/ Ankerite	Pyrite
	|------CALCULATED WEIGHT PERCENTS (WEIGHT FACTORS DIVIDED BY I/Icor VALUES):					
R1	25.9	3.0	5.2	65.4	0.5	-
R2	20.5	2.3	5.4	71.0	0.9	-
R3	25.5	3.1	5.9	64.9	0.5	-
R4	14.0	1.9	7.0	76.5	0.7	-
R5	22.7	2.2	5.3	69.3	0.5	-
R6	20.5	2.3	5.4	71.2	0.5	-
R7	4.3	-	0.9	94.8	-	-
R8	10.7	0.9	6.2	81.6	0.6	-
R9	22.3	3.1	5.2	68.1	1.3	-
R10	6.7	1.0	7.7	84.7	-	-
R11	4.0	2.8	6.6	86.7	-	-
R12	15.1	1.9	5.8	76.7	0.6	-
R13	16.4	1.7	7.8	73.5	0.7	-
R14	9.4	2.0	7.4	81.3	-	-
R15	21.6	3.1	6.2	68.6	0.5	-
R16	25.7	1.2	-	72.6	0.6	-
R17	22.2	3.1	6.2	67.9	0.6	-
R18	24.7	2.3	-	72.4	0.6	-
R19	1.0	1.6	-	96.7	0.7	-
R20	18.5	2.5	-	78.3	0.7	-
R21	12.1	1.0	8.2	77.3	1.4	-
R22G	7.5	2.0	7.5	82.3	0.6	-
R22R	21.8	3.0	8.1	66.6	0.5	-
R23	9.3	-	0.0	88.5	2.2	-
R24	7.3	-	8.7	81.9	2.1	-
R25	6.1	1.1	-	92.9	-	-
R27	24.7	4.1	6.7	62.9	1.6	-

CALCULATION OF MINERAL WEIGHT PERCENTS IN BULK ROCK SAMPLES FROM WEIGHT FRACTIONS AND I/I CORUNDUM VALUES

Geologist: Judy Musselman
Sample No: R1 to R 48
West Spring Creek data
Sample Type: Carbonate

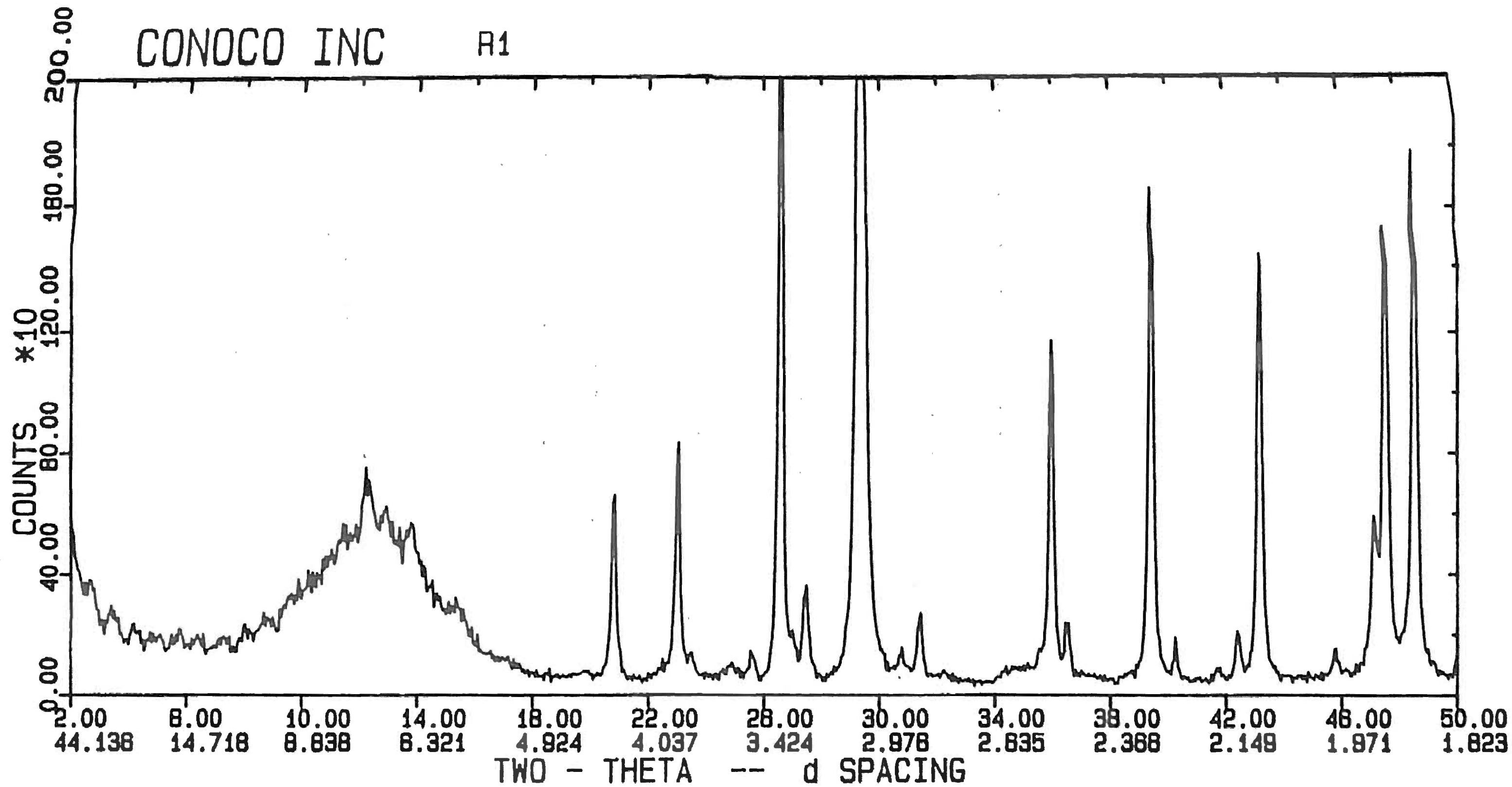
Project: Thesis - X-Ray Results

	|------CALCULATED WEIGHT PERCENTS (WEIGHT FACTORS DIVIDED BY I/Icor VALUES):					
Sample Number	Quartz	Potassium Feldspar	Total Clay	Calcite	Dolomite/ Ankerite	Pyrite
R28	11.8	2.4	8.0	75.0	2.9	-
R30	13.5	8.4	60.7	12.9	4.4	-
R31	17.6	7.9	12.9	61.0	0.6	-
R31.1	5.8	-	6.7	63.0	-	24.5
R32	18.8	0.4	4.8	44.8	31.3	-
R32.1	3.4	-	6.6	87.7	2.2	-
R33	8.5	1.8	48.9	40.4	0.4	-
R34	16.0	2.6	-	81.4	-	-
R35	24.5	1.7	-	71.9	1.8	-
R36	33.5	4.1	19.4	42.7	0.3	-
R37	22.7	8.5	37.5	30.9	0.4	-
R38	20.3	3.6	20.1	55.4	0.6	-
R39	20.8	4.3	8.0	66.1	0.8	-
R40	9.6	0.5	8.6	29.7	51.6	-
R41	14.2	1.1	0.0	83.6	1.1	-
R42	7.0	0.8	6.4	9.1	76.8	-
R42.1	14.4	3.9	18.5	60.9	2.3	-
R43	22.2	3.2	8.9	65.1	0.7	-
R43.1	18.1	4.1	14.3	62.8	0.7	-
R44	20.1	0.9	8.5	69.7	0.8	-
R46	21.4	4.3	40.5	33.4	0.4	-
R47	18.3	2.3	29.3	48.2	1.8	-
R48	11.2	1.0	9.4	77.7	0.7	-



KEY :

CL - CLAYS Q - QUARTZ C - CALCITE A - ANKERITE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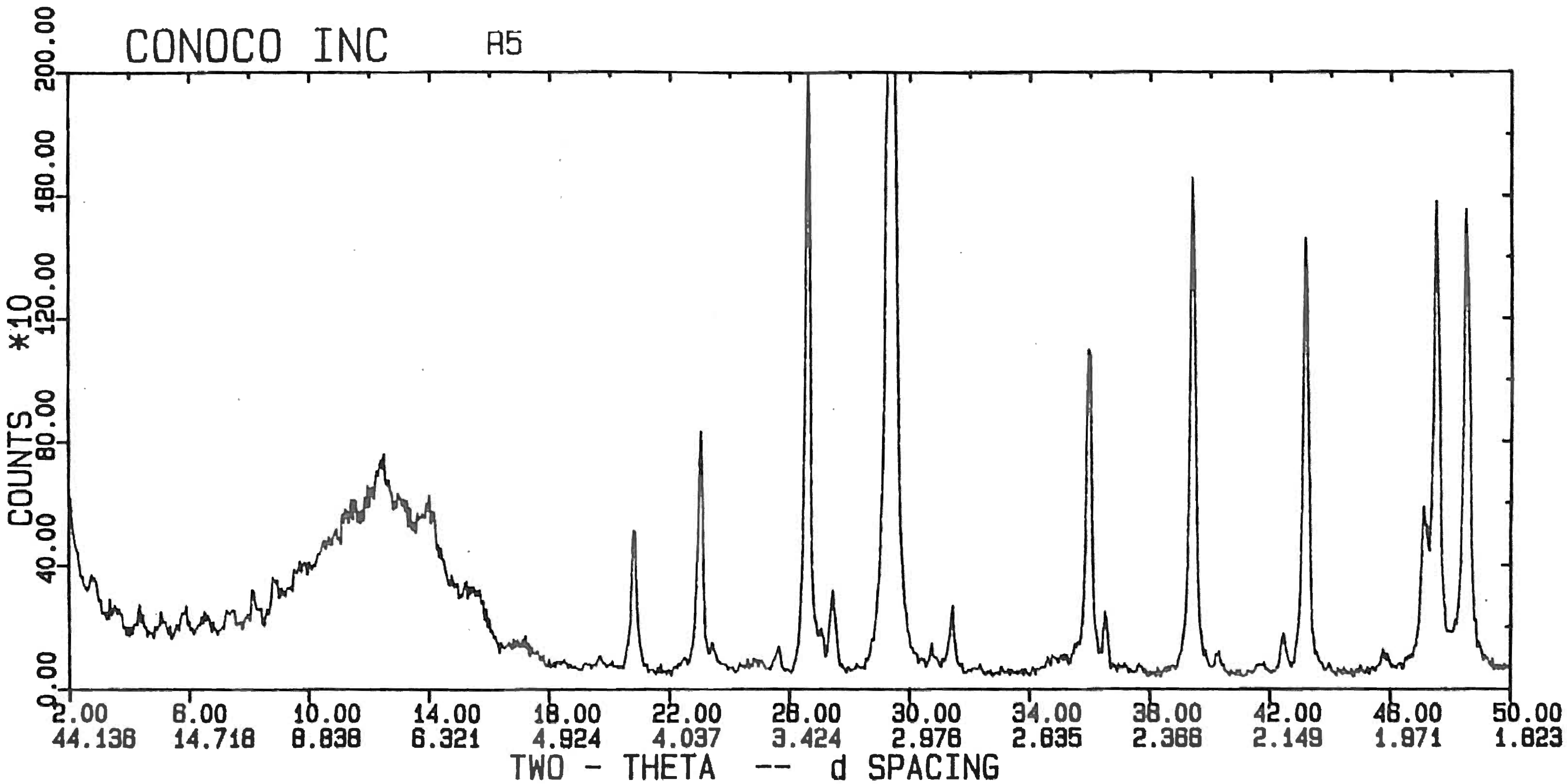
R1
COUNTS *10
TWO - THETA -- d SPACING



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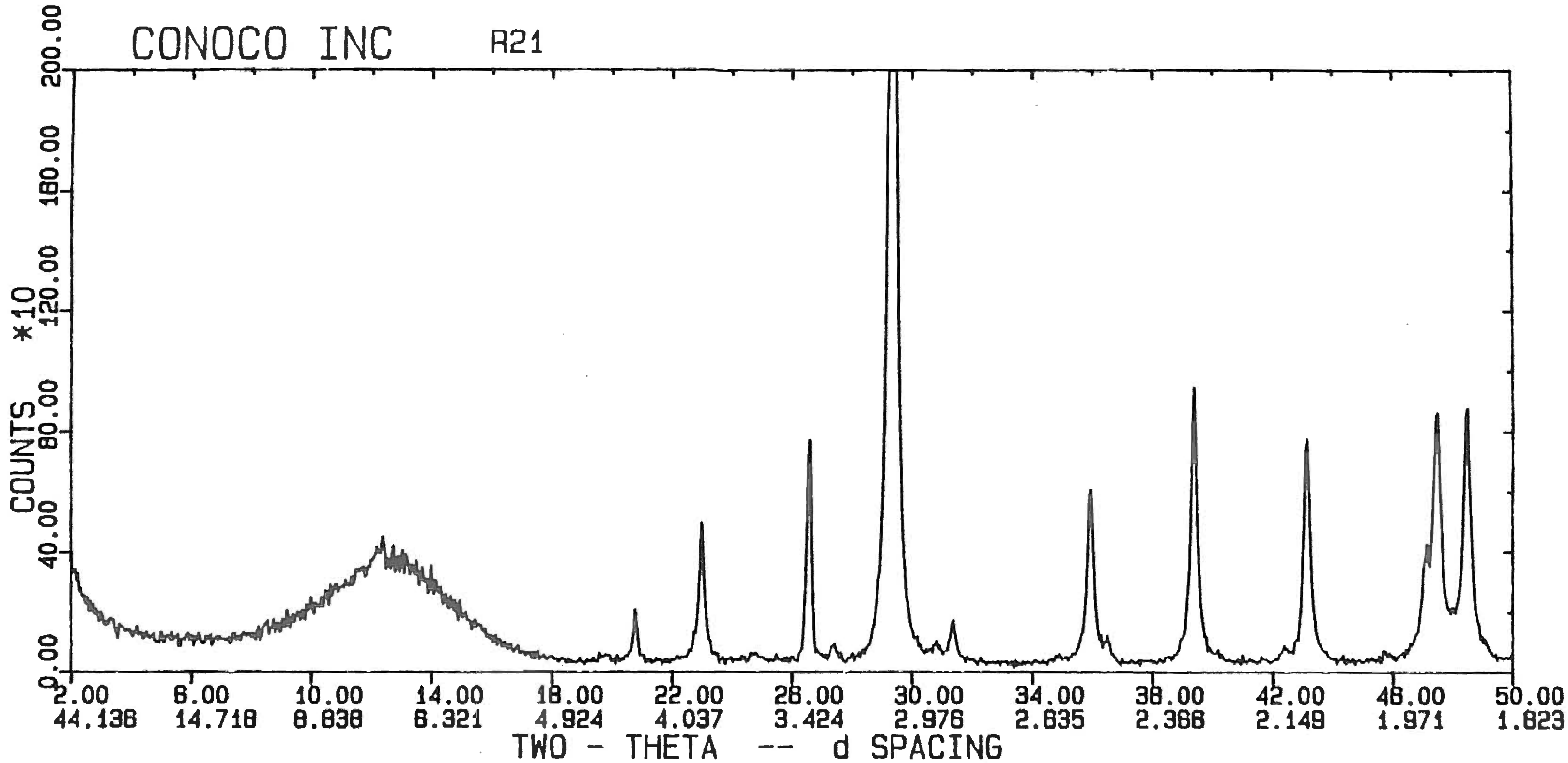
160.00
200.00
2.00 44.138
6.00 14.718
10.00 8.838
14.00 6.321
18.00 4.924
22.00 4.037
26.00 3.424
30.00 2.976
34.00 2.635
38.00 2.366
42.00 2.149
46.00 1.971
50.00 1.823
TWO - THETA -- d SPACING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2.00
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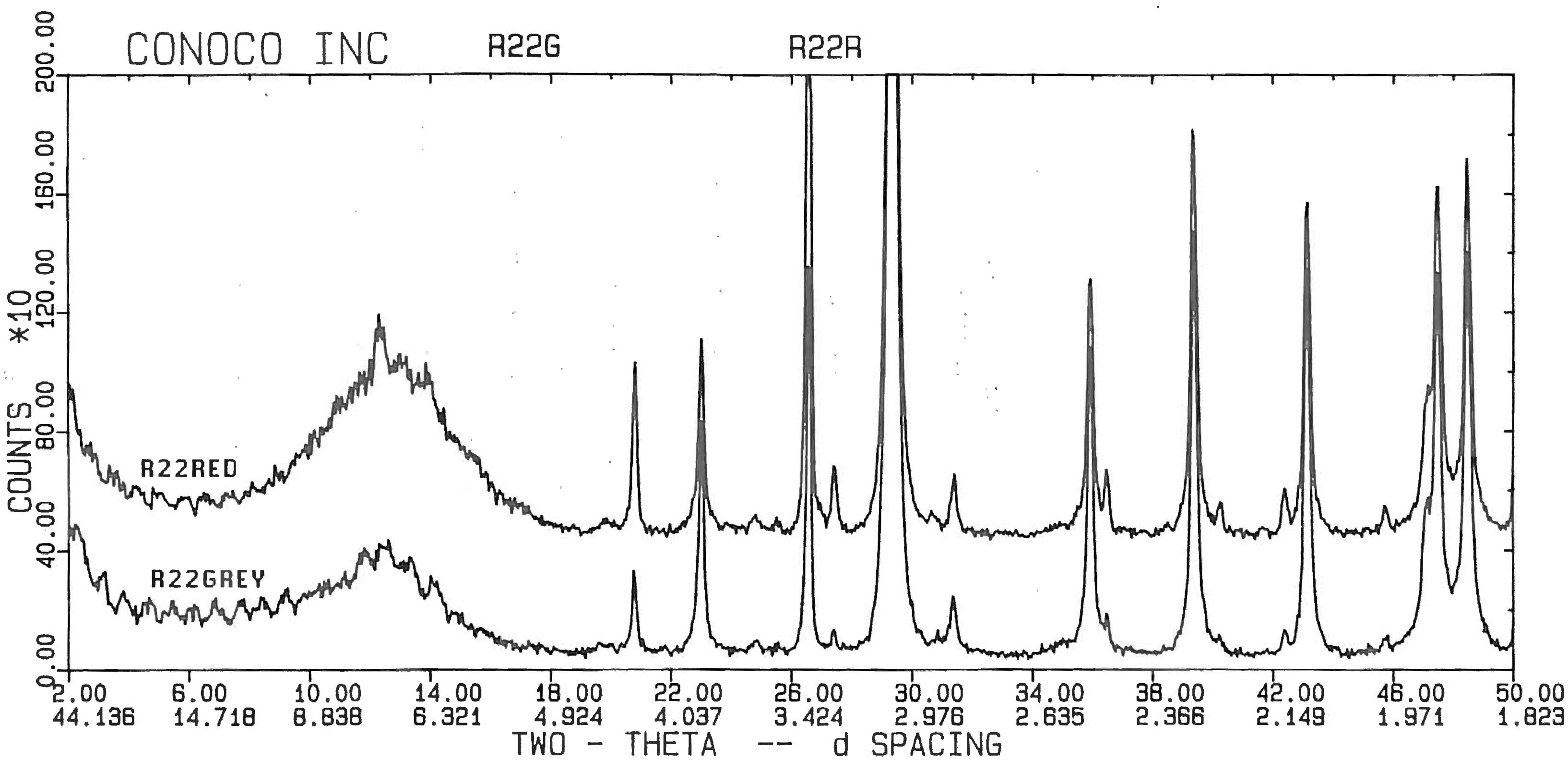
10.00
8.838
14.00
6.321
18.00
4.924
22.00
4.037
26.00
3.424
30.00
2.976
34.00
2.635
38.00
2.366
42.00
2.149
46.00
1.971
50.00
1.823
TWO - THETA -- d SPACING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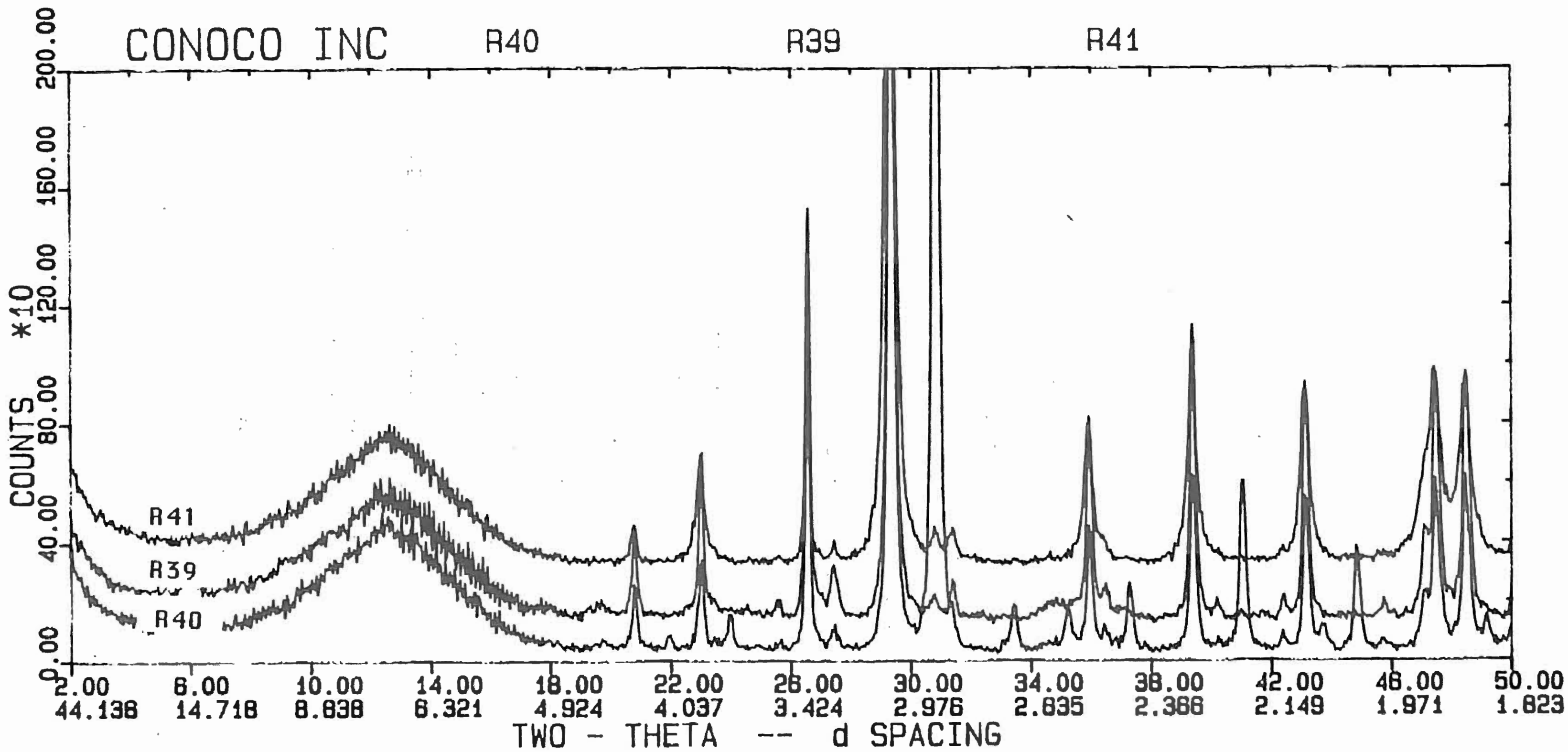
R22G
R22R
200.00
160.00
120.00
80.00
40.00
0.00
COUNTS *10
R22RED
R22GREY
2.00 44.136
6.00 14.718
10.00 8.838
14.00 6.321
18.00 4.924
22.00 4.037
26.00 3.424
30.00 2.976
34.00 2.635
38.00 2.366
42.00 2.149
46.00 1.971
50.00 1.823
TWO - THETA -- d SPACING


CONOCO INC
R40
R39
R41
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120.00
80.00
40.00
0.00
COUNTS *10
R41
R39
R40
2.00
44.138
6.00
14.718
10.00
8.838
14.00
6.321
18.00
4.924
22.00
4.037
26.00
3.424
30.00
2.976
34.00
2.635
38.00
2.366
42.00
2.149
46.00
1.971
50.00
1.823
TWO - THETA -- d SPACING

VITA 2

Judith Lynn Musselman

Candidate for the Degree of

Master of Science

Thesis: PALEOKARSTIC PHENOMENA, DEPOSITIONAL ENVIRONMENTS, AND DIAGENESIS OF THE LOWER ORDOVICIAN WEST SPRING CREEK FORMATION, ARBUCKLE GROUP, IN SOUTHERN OKLAHOMA

Major Field: Geology

Biographical:

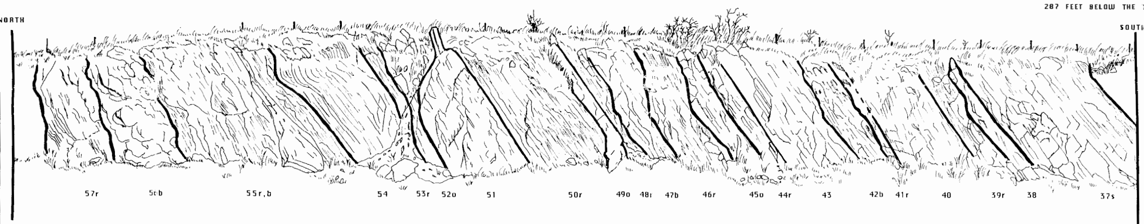
Personal Data: Born in Tonkawa, Oklahoma, on March 27, 1938, the daughter of Irene Elizabeth Musselman and Charlie Clark Musselman

Education: Graduated from Tonkawa High School, Tonkawa, Oklahoma in June 1956; received an Associate's degree from Northern Oklahoma Junior College, Tonkawa, Oklahoma in June 1958; received a Bachelor of Science degree in Geology with a minor in Geography from Oklahoma State University, Stillwater, Oklahoma in May 1987. Completed the requirements for the Master of Science degree with a major in Geology at Oklahoma State University in May 1994.

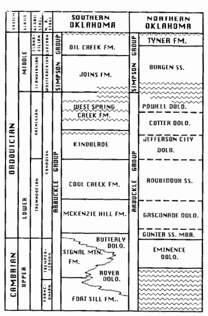
Experience: Employed by Conoco Inc., Ponca City, Oklahoma, in Computer Informations Systems Department for 25 years; currently classed as a computer operator; employed by Oklahoma State University, Department of Geology as a research assistant and as a teaching assistant.

Professional Affiliations: Gamma Theta Upsilon, American Association of Petroleum Geologists, Oklahoma City Geological Society Discussion Group, Scholar-Leadership Enrichment Program.

APPROXIMATELY 1/8 MILE NORTH
OF MILE MARKER 45
287 FEET BELOW THE TOP OF THE ARBUCKLE



STRATIGRAPHIC SECTION



BED DESCRIPTIONS

NUMBERING SYSTEM CORRESPONDS
TO FAY'S 1969 MEASURED SECTION

KEY: (SYMBOL FOLLOWING BED NUMBER)
S = SANDSTONE
R = RED BED
B = BRECCIA
O = OOLITE

37S	8 FEET OF WHITE TO TAN SANDSTONE
38	1 FOOT OF TAN DOLOMITIC LIMESTONE
39R	TWO FEET OF RED-BROWN MARL AND SHALE
40	5 FEET OF LAVENDER LIMESTONE, MARL AND SHALE
41R	1 1/2 FEET OF RED-BROWN SHALE AND LIMESTONE
42B	2 FEET OF YELLOW-BROWN TO GREENISH-GREY DOLOMITIC LIMESTONE AND BRECCIA
43	5 1/2 FEET OF GREY TO TAN LIMESTONE
44R	2 FEET YELLOW TO PINK LIMESTONE AND SHALE
45O	3 FEET OF GREY OOLITIC LIMESTONE
46R	3 FEET OF REDDISH-BROWN MARL AND SHALE
47B	1 FOOT OF GREY LIMESTONE AND PARABRECCIA
48R	1 7/10 FEET OF MARL AND LIMESTONE
49O	1 1/2 FEET OF OOLITIC LIMESTONE
50R	6 8/10 FEET OF RED, GREY, OR YELLOW MARL, LIMESTONE AND SHALE
51	6 FEET OF GREY LIMESTONE
52O	9/10 FEET OF GREY OOLITIC LIMESTONE
53R	1 2/10 FEET OF REDDISH-BROWN MARL
54	3 1/2 FEET OF GREY LIMESTONE
55RB	12 1/2 FEET OF REDDISH-BROWN LIMESTONE AND MARL WITH GREY COLLAPSE BRECCIA IN MIDDLE
56B	4 1/2 FEET OF COLLAPSE BRECCIA AND PARABRECCIA
57R	5 FEET OF TAN TO LAVENDER LIMESTONE, SHALE AND MARL

UPPER RED BED SEQUENCE
WEST SPRING CREEK FORMATION
ARBUCKLE GROUP

CARTER COUNTY, OKLAHOMA
INTERSTATE 35 OUTCROPS
77.6 FEET OF SECTION

ORIGINAL SECTION MEASURED BY ROBERT O. FAY (1969)

PLATE 1

UPPER RED BED SEQUENCE
OUTCROP SECTION
INTERSTATE 35

JUDITH L. MUSSELMAN M. S. THESIS 1994
OKLAHOMA STATE UNIVERSITY